RASKOFF ENVIRONMENTAL SCIENCE



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Introduction to 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 a 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.

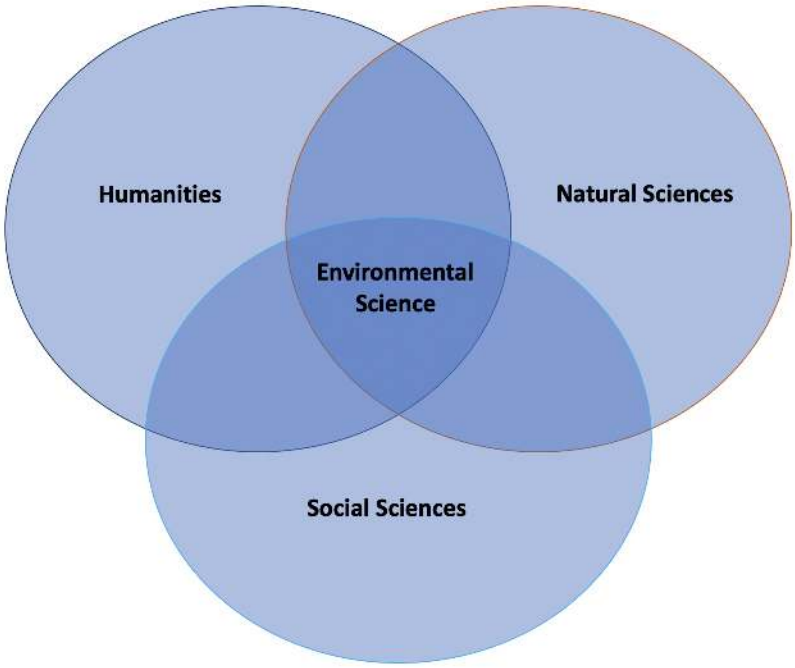


Figure 1.1.*a*: Venn diagram illustrating how environmental science is interdisciplinary between humanities, natural sciences (which includes physical and life sciences) and social sciences. Image by Rachel Schleiger (CC-BY-NC).

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.

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 the intensive use of forests and unregulated access.
- **Soil** — As much as 10% of the earth's vegetated surface is now at least moderately degraded. Trends in soil quality and management of irrigated land raise serious questions about longer-term sustainability. It is estimated that about 20% of the world's 250 million hectares of irrigated land are already degraded to the point where crop production is seriously reduced.
- **Fresh water** — Some 20% of the world's population lacks access to safe water and 50% lacks access to safe sanitation. If current trends in water use persist, two-thirds of the world's population could be living in countries experiencing moderate or high water stress by 2025.
- **Marine fisheries** — 25% of the world's marine fisheries are being fished at their maximum level of productivity and 35% are overfished (yields are declining). In order to maintain the 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 by military activities involving nuclear materials.
- **Waste** — Domestic and industrial waste production continues to increase in both absolute and per capita terms, worldwide. In the developed world, per capita waste generation has increased threefold over the past 20 years; in developing countries, 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 are still some of the principal causes of death and disability for the urban poor.

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1.2: Introduction to Sustainability

Cities in today's modern world are struggling to balance a sustainable society, economy, and environment. According to a 2016 report that rated sustainability across 32 indicators, Zurich, Switzerland, was ranked number one. Zurich invests in renewable energies, sustainable public transport, public green space, and public education. One of the most notable ways Zurich is leading global sustainability efforts is its dedication to keeping its carbon dioxide emissions low. Figure 1.2.1 below shows the difference in emissions for the United States and Switzerland:

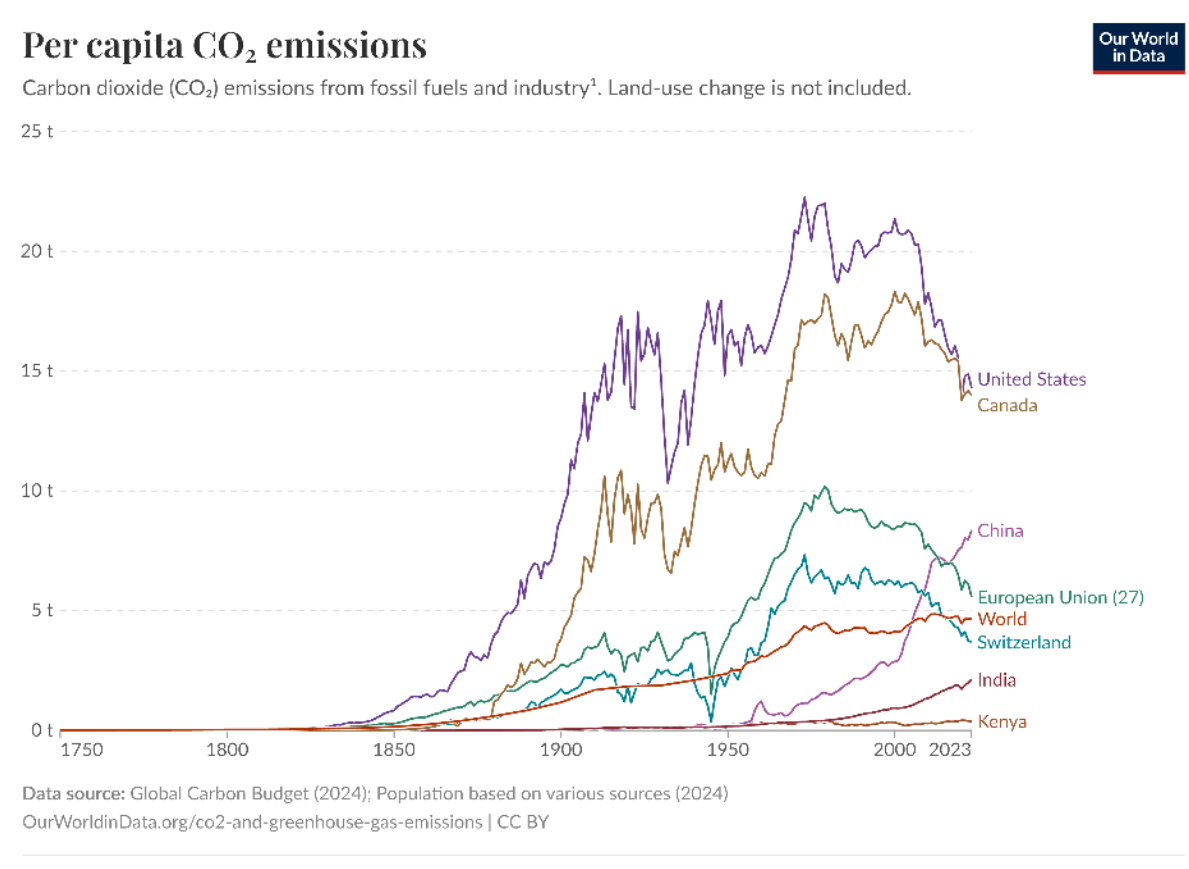


Figure 1.2.1: Per capita emissions of carbon dioxide between the United States and Switzerland. Graph by Our World in Data (CC-BY4.0)

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, competencies, 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 waste.
- 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 1.2.2).

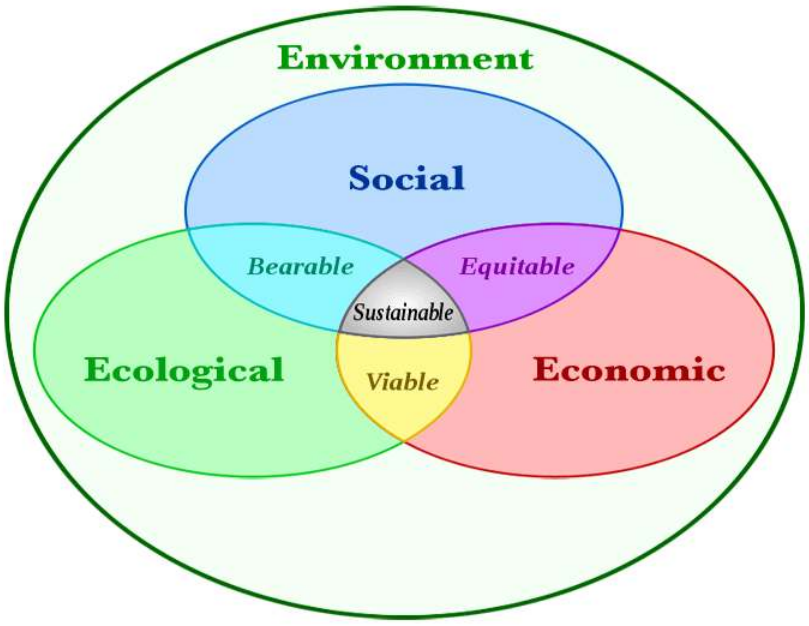


Figure 1.2.2: Venn diagram of defining the components of sustainability. Image by Andrew, Sunray, based on "File:Sustainable development.svg" by Johann Dréo in Wikimedia Commons (CC-BY-SA4.0)

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, 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.

The Evolution of Sustainability

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

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

The concept of sustainability, however, can be traced back much farther to the oral histories of indigenous cultures. For example, the principle of inter-generational equity is captured in the Inuit saying, ‘we do not inherit the Earth from our parents, we borrow it from our children’. The Native American ‘Law of the Seventh Generation’ is another illustration. According to this, before any major action was to be undertaken its potential consequences on the seventh generation had to be considered. For a species that at present is only 6,000 generations old and whose current political decision-makers operate on time scales of months or few years at

most, the thought that other human cultures have based their decision-making systems on time scales of many decades seems wise but unfortunately inconceivable in the current political climate.

Environmental Equity

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

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

Ecological Footprint

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

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

WHAT IS YOUR CARBON FOOTPRINT? There are many personal calculators available on the internet. Here are a few to try:

- EPA Household Emissions Calculator
- Cool Climate Network (UC Berkeley)
- Carbon Footprint

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

For more information on ecological footprints see the Living Planet Report by the World Wildlife Fund, Zoological Society of London, and The Global Footprint Network. You can find the 2020 Living Planet Report as well as summaries on the Global Footprint Network website.

The IPAT Equation

As attractive as the concept of sustainability may be as a means of framing our thoughts and goals, its definition is rather broad and difficult to work with when confronted with choices among specific courses of action. Here we introduce one general way to begin to apply sustainability concepts: the IPAT equation. As is the case for any equation, IPAT expresses a balance among interacting factors. It can be stated as:

$$I=P\times A\times T$$

where *I* represents the **impacts** of a given course of action on the environment, *P* is the relevant human **population** for the problem at hand, *A* is the level of **consumption** per person, and *T* is the **impact** per unit of consumption. Impact per unit of consumption is a general term for technology, interpreted in its broadest sense as any human-created invention, system, or organization that serves to either worsen or uncouple consumption from impact. The equation is not meant to be mathematically rigorous; rather it provides a way of organizing information for a "first-order" analysis.

The Precautionary Principle

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

Natural Resources

All natural resources (also known as natural capital) can be divided into two categories: non-renewable and renewable.

Non-Renewables

Non-renewable resources are present in a finite quantity and do not regenerate after they are harvested and used. Consequently, as non-renewable resources are used, their remaining stocks in the environment are depleted. This means that non-renewable resources can never be used in a sustainable fashion – they can only be "mined" (figure 1.2.3). Examples of non-renewable resources include metal ores, petroleum, coal, and natural gas. Although continuing exploration may discover additional stocks of non-renewable resources that can be exploited, this does not change the fact that there is a finite quantity of these resources present on Earth. For example, the discovery of a large amount of metal ore in a remote place may substantially increase the known, exploitable reserves of those non-renewable materials. That discovery does not, however, affect the amounts of the metal present on Earth.

Metals are often used to manufacture parts of buildings and machinery. To some degree, the metals can be recovered after these uses and recycled back into the economy, effectively extending the lifespan of their reserves. However, due to the growth and increasing industrialization of the economy, the demand for metals is accelerating. Because recycling cannot keep up with the increasing demands for metals, large additional quantities must be mined from their known reserves in the environment. For valuable metals, such as gold and platinum, there is a high efficiency of recycling, but it is much less so for iron and other less-costly metals.

Fossil fuels are the other major category of non-renewable resources. They are mostly combusted to provide energy for transportation and heating, which converts their organic compounds into carbon dioxide and water, which are released into the environment. Some of that CO_2 and H_2O may be absorbed by plants and other photosynthetic organisms and be converted back into organic materials, a process that might be interpreted as a kind of recycling. However, the rate at which this happens is insignificantly small compared with the release of CO_2 and H_2O by the combustion of fossil fuels, so these materials should be viewed as being as non-renewable as metals are. A more minor use of fossil fuels is to manufacture various kinds of plastics. These synthetic materials can be recycled after initial uses, which does help to extend the lifespan of the reserves of fossil fuels. Nevertheless, because the dominant use of fossil fuels is as source of energy, they essentially flow through an industrial economy, with little new recycling.

> *Figure 1.2.3: Non-renewable resources can only be mined. This is a view of the Etaki open-pit diamond mine in the Northwest Territories. Three open pits can be seen as a cluster, plus another at the top-left of the image, along with an extensive tailings-disposal area and other infrastructure. Source: Jason Pineau, Wikimedia Commons; http://commons.wikimedia.org/wiki/File:Ekati_mine_640px.jpg .*



Renewables

Renewable resources are capable of regenerating after harvesting, so potentially their stocks can be utilized forever. Most renewable resources are biological (Figure 1.2.4, although some are non-biological. **Biological Renewable Resources** Renewable resources that are biological in nature (bio-resources) include the following:

- wild animals that are hunted as food or for bio-materials, such as deer, moose, hare, ducks, fish, lobster, and seals
- forest biomass that is harvested for lumber, fiber, or energy
- wild plants that are gathered as sources of food
- plants cultivated as sources of food, medicine, materials, or energy
- the organic-based capability of soil to sustain the productivity of agricultural crops

Figure 1.2.4: Renewable resources, such as timber and fish, are capable of regenerating after they are harvested. Provided they are not over-harvested or managed inappropriately, renewable resources can be harvested in a sustainable fashion. This photo shows a load of timber that was harvested on Vancouver Island. Source: B. Freedman.



Non-Biological Renewable Resources The following are renewable resources that are non-biological:

- sunlight, of which there is a continuous input to Earth
- surface water and groundwater, which are renewed through the hydrologic cycle
- winds, which are renewed through the heat-distribution system of the atmosphere
- water currents and waves, which are renewed through the heat-distribution system of the oceans, as well as the tidal influence of the Moon

Many renewable resources can be managed to increase their rates of recruitment and productivity and to decrease mortality. In the following section we explain how management practices can be used to increase the productivity of biological resources. Although a renewable resource can regenerate after harvesting, it can also be badly degraded by excessive use or by inappropriate management. These practices can damage the ability to regenerate and may ultimately cause a collapse of the stock. If this happens, the renewable resource is being “mined”, or used as if it were a non-renewable resource. As such, it becomes depleted by excessive use. For this reason, ecologists commonly use the qualified term: potentially renewable resources.

Sustainable Living

Sustainable living describes a lifestyle that attempts to reduce/eliminate an individual's (or society's) use of resources so as to be as close as possible to "net zero living". As such, an individual (or society) focuses on reducing their footprint (ecologically, carbon, socially, etc) through their choices/methods of:

- Use of resources (energy/diet/transportation/water/etc)
- Support of people/companies (voting/economic/social/etc)
- Practices of reducing, reusing, and recycling
- Consciousness of priority and focus on local concerns/needs versus global concerns/needs
- Sharing knowledge with their community (all ages)

The thought of getting started with sustainable living can be overwhelming! However, it is important to note that although we can acknowledge all the things that need to be accomplished, that entire burden does not lie with just one individual's control (Figure 1.2.5). It takes a multi-layerd approach to appropriately take action at the individual, societal, and political levels (Figure 1.2.6).

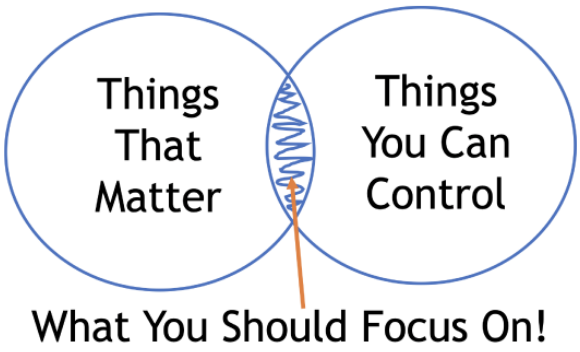


Figure 1.2.5: Focus for individual sustainability lifestyle goals. Image by Rachel Schleiger (CC-BY-NC)



Figure 1.2.6: Considerations for sustainable living goals. Image by Sustainability Week Switzerland in Wikimedia Commons (CC-BY-SA)

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1.3: Environmental Ethics and Environmental Justice

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 herdsman 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 herdsman 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 herdsman 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 ruination of the commons. In a society that believes in the freedom of the commons, freedom brings ruin to all because each person acts selfishly. His pessimistic view, although critiqued by many, has been very influential in our thinking about the problems inherent in managing unowned, or public resources. The tragedy of the commons describes a situation where individuals acting in their own self-interest deplete a shared resource, even when it's clear that doing so is detrimental to the group as a whole. This happens because each individual benefits from using the resource, while the negative consequences of overuse are shared by everyone. The short-term gain for individuals outweighs the long-term damage to the shared resource.

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

The "Tragedy of the Commons" is applicable to what is arguably the most consequential environmental problem: global climate change. The atmosphere is a common pool 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 on 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.

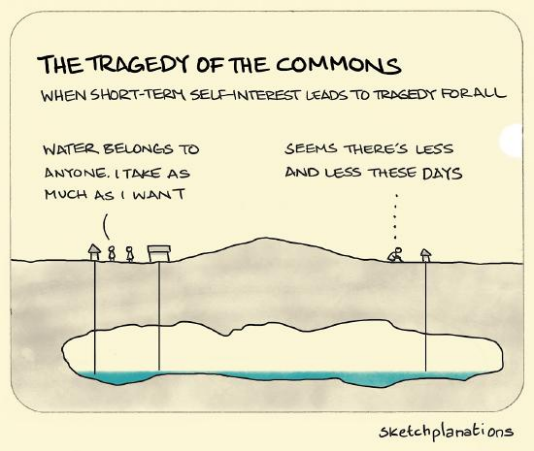


Figure 1.3.1: The tragedy of the commons. Image: Jono Hey, Sketchplanations.



Figure 1.3.2: Nobel Laureate in Economics, Elinor Ostrom, a fierce critic of Hardin's ideas.

Criticism of the "Tragedy" of the Commons

Hardin's inflexible and pessimistic ideas on the inevitability of the "tragedy" have had many critics, including the Nobel Laureate in Economics, Elinor Ostrom. The main criticism is that it overgeneralizes and misrepresents how people actually manage shared resources. Critics argue that Hardin misunderstood the historical concept of “commons.” In many traditional societies, commons were effectively managed through local rules, customs, and collective governance, not left open to unregulated exploitation or privatization. Hardin suggested that only privatization or government regulation could prevent resource depletion. However, scholars like Ostrom demonstrated that communities can sustainably manage shared resources through cooperation, trust, and self-governance. It is often assumed that all users are equal, ignoring how wealth, power, and politics influence access and exploitation of resources. In reality, overuse often results from a powerful few rather than collective misuse by all. The idea implies that individuals will always act selfishly in shared-resource situations, ignoring the many examples of collective action, stewardship, and sustainable practices. In short, the criticism is that the "Tragedy of the Commons" simplifies complex social, cultural, and political dynamics, underestimating human capacity for cooperation and sustainable resource management.

Environmental Ethics

The concept of **ethics** involves standards of conduct. These standards help to distinguish between behavior that is considered right and that which is considered wrong. As we all know, it is not always easy to distinguish between right and wrong, as there is no universal code of ethics. For example, a poor farmer clears an area of rainforest in order to grow crops. Some would not oppose this action, because the act allows the farmer to provide a livelihood for his family. Others would oppose the action, claiming that deforestation will contribute to soil erosion and global warming. Right and wrong are usually determined by an individual's morals, and to change the ethics of an entire society, it is necessary to change the individual ethics of a majority of the people in that society.

Moral extensionism defines how far a person's values extend outside of themselves (Figure 1.3.3). There are many variables that can influence where the limit lies for each individual person. For example, religion, culture, education, and personal interests (just to name a few).



Figure 1.3.3: Scope of consideration for moral extensionism. Image by Rachel Schleiger (CC-BY-NC).

Frontier Ethic

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

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

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

Sustainable Ethic

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

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

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

Land Ethic

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

"The **land ethic** simply enlarges the boundary of the community to include soils, waters, plants, and animals; or collectively, the land. In short, a land ethic changes the role of *Homo sapiens* from conqueror of the land-community to plain member and citizen of

it. It implies respect for his fellow members, and also respect for the community as such." (Aldo Leopold, 1949)

Leopold divided conservationists into two groups: one group that regards the soil as a commodity and the other that regards the land as biota, with a broad interpretation of its function. If we apply this idea to the field of forestry, the first group of conservationists would grow trees like cabbages, while the second group would strive to maintain a natural ecosystem. Leopold maintained that the conservation movement must be based upon more than just economic necessity. Species with no discernible economic value to humans may be an integral part of a functioning ecosystem. The land ethic respects all parts of the natural world regardless of their utility, and decisions based upon that ethic result in more stable biological communities.

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

Hetch Hetchy Valley

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



Figure 1.3.4. Yosemite valley, California, USA.

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

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

> *"As to my attitude regarding the proposed use of Hetch Hetchy by the city of San Francisco…I am fully persuaded that… the injury…by substituting a lake for the present swampy floor of the valley…is altogether unimportant compared with the benefits to be derived from it's use as a reservoir.*
>
> *"The fundamental principle of the whole conservation policy is that of use, to take every part of the land and its resources and put it to that use in which it will serve the most people." (Gifford Pinchot, 1913)*

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

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

Despite public protest, Congress voted to dam the valley. The preservationists lost the fight for the Hetch Hetchy Valley, but their questioning of traditional American values had some lasting effects. In 1916, Congress passed the "National Park System Organic Act," which declared that parks were to be maintained in a manner that left them unimpaired for future generations. As we use our public lands, we continue to debate whether we should be guided by preservationism or conservationism.

Environmental Justice

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

Whenever a community is faced with the potential of an environmentally undesirable facility, such as the placement of a hazardous waste dump in its midst, the usual response from residents is: "Not in my backyard!" Such a response is known as the NIMBY principle. Such reactions are usually reactions to visions of previous environmental irresponsibility: uncontrolled dumping of noxious industrial wastes and rusty steel drums oozing hazardous chemicals into the environment. Such occurrences were all too real in the past and some are still taking place. It is now possible -- and much more common -- to build environmentally sound, state-of-the-art disposal facilities. However, the NIMBY principle usually prevents the construction of such new facilities. Instead, hazardous waste facilities tend to be built upon pre-existing, already contaminated sites, even though the geology of such locations may be less favorable for containment than potential new sites.

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

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

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

Indigenous People

Since the end of the 15th century, most of the world's frontiers have been claimed and colonized by established nations. Invariably, these conquered frontiers were home to people indigenous to those regions. Some were wiped out or assimilated by the invaders, while others survived while trying to maintain their unique cultures and way of life. The United Nations officially classifies **indigenous people** as those "having an historical continuity with pre-invasion and pre-colonial societies," and "consider

themselves distinct from other sectors of the societies now prevailing in those territories or parts of them." Furthermore, indigenous people are "determined to preserve, develop and transmit to future generations, their ancestral territories, and their ethnic identity, as the basis of their continued existence as peoples in accordance with their own cultural patterns, social institutions, and legal systems." A few of the many groups of indigenous people around the world are: the many tribes of Native Americans (i.e., Navajo, Sioux) in the contiguous 48 states, the Inuit of the arctic region from Siberia to Canada, the rainforest tribes in Brazil, and the Ainu of northern Japan.

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

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



Figure 1.3.5. An Inupiaq woman, Nome, Alaska, c. 1907. Credit: This work is in the Public Domain, CC0

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

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1.4: Environmental Policy

Introduction

It is not uncommon 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 Brundtland Report) when it was first presented in 1987. However, it would be a mistake to conclude that sustainability as a mental construct and policy framework for envisioning the relationship of humans and nature came into being suddenly and at a single moment in time. Most environmental historians who have studied U.S. policy have discerned at least three distinct periods during which new concepts and ideas, scientific understandings, technological advances, political institutions, and laws and regulations came or were brought into being in order to understand and manage human impacts on the environment.

1. **The American conservation movement:** This 19th century movement had the main objective for conservation of American land and resources, it grew from opposite philosophies. On one side you had people like Gifford Pinchot (first head of the US National Forest Service) that were very pragmatic about their desire for conservation. For example, these people observed that policies for harvesting some resource (like lumber) were not sustainable, so they began conservation/sustainability research and new policies so the resource would not run out in the foreseeable future. On the other side were people like John Muir and Theodore Roosevelt that saw land/habitats/wildlife as intrinsic entities, meaning that had value in their own right (meaning nothing to do with money).
2. **The rise of environmental risk management as a basis for policy:** 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. In addition, environmental scientists of the day were 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, 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.
3. **The integration of social and economic factors to create what we now refer to as the sustainability paradigm:** Eventually, we (humanity) realized that in order to solve environmental issues (like ones identified by Rachel Carson), that the "human factors" (both social and economical) had to be accounted for. This is what defines the sustainability paradigm: environmental, social, and economic disciplines. Only Band-Aid solutions can be applied if we only take a one-minded approach.

History of Environmental Policy

Environmental policies are typically driven by problems of the day, real and perceived, that require systemic solutions. For example:

- Early conservationists were alarmed at the inefficiencies of human resource management and the encroachment of humans on unspoiled lands... Leading to conservation legislation.
- 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... Leading to clean air and water legislation.
- 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 1.4.*a*: Table illustrating evolution of environmental policy. Table by Sustainability: A Comprehensive Foundation in Openstax (CC-BY).

	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 anthropocentric and 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
Conceptual Model	Expansion vs preservation	Command and control	Systems/life cycle approach
Disciplinary Approach	Disciplinary and insular	Multidisciplinary	Interdisciplinary/integrative

Table 1.4.*b*: Table illustrating major environmental legislation, society, and organization conceptions. Table by Rachel Schleiger (CC-BY-NC).

Year	Policy/Society/Organization Conception
1899	Refuse Act
1905	National Forest Service
1916	National Park Service
1918	Migratory Bird Treaty Act
1930's	State Parks
1948	Federal Water Pollution Control Act
1950	The Nature Conservancy
1955	Air Pollution Control Act
1961	World Wildlife Federation
1963	Clean Air Act (1970, 1977, 1990 updates)
1965	Solid Waste Disposal Act (1976 update)
1965	Water Quality Act (1987 update)
1967	Air Quality Act
1969	National Environmental Policy Act
1970	Occupational Safety and Health Act
1970	Environmental Protection Agency
1971	Occupational Safety and Health Administration
1972	Consumer Product Safety Act
1972	Federal Insecticide, Fungicide, and Rodenticide Act
1972	Clean Water Act (1977 update)
1972	Noise Control Act
1973	Endangered Species Act
1974	Safe Drinking Water Act (1986, 1996 updates)
1975	Hazardous Materials Transportation Act
1976	Resource Conservation and Recovery Act
1976	Toxic Substances Control Act
1980	CERCLA (Superfund)
1984	Hazardous and Solid Waste Amendments
1986	Superfund Amendments and Reauthorization Act
1986	Emergency Wetlands Resources Act
1990	Oil Pollution Act
1993	North American Free Trade Agreement
2003	Healthy Forest Initiative

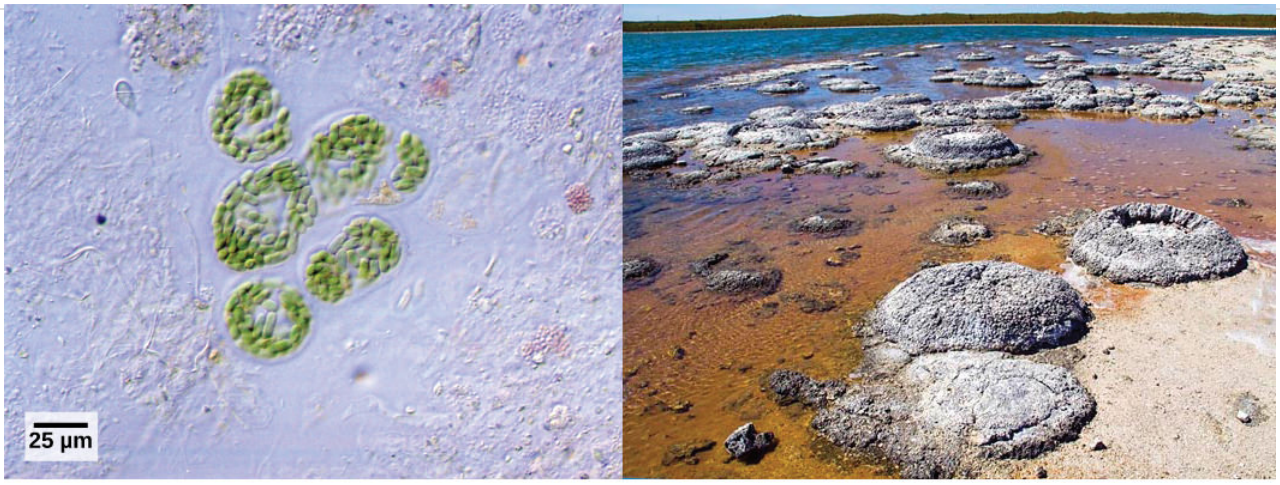
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1.5: The Process of Science



(a) (b)

Figure 1.5.1. (a) The cyanobacteria seen through a light microscope are some of Earth's oldest life forms. These (b) stromatolites along the shores of Lake Thetis in Western Australia are ancient structures formed by the layering of cyanobacteria in shallow waters. (Credit a: modification of work by NASA; scale-bar data from Matt Russell; credit b: modification of work by Ruth Ellison)

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

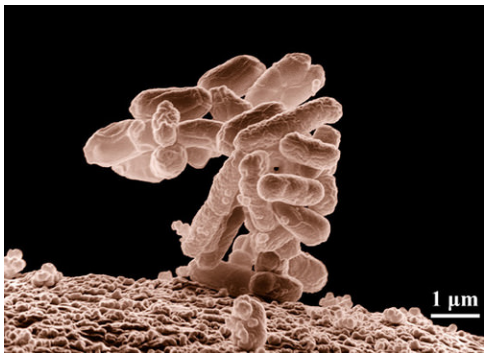


Figure 1.5.2. Biologists may choose to study Escherichia coli (E. coli), a bacterium that is a normal resident of our digestive tracts but which is also sometimes responsible for disease outbreaks. In this micrograph, the bacterium is visualized using a scanning electron microscope and digital colorization. (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 a process of gaining knowledge about the natural world.

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

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

Natural Sciences

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

Scientific Inquiry

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

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

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

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

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

Hypothesis Testing

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



Figure 1.5.3. 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. **Experimental variables** are any part of the experiment that can vary or change during the experiment. **Controlled variables** are parts of the experiment that do not change. Lastly, experiments might have a **control group**: a group of test subjects that are as similar as possible to all other test subjects, with the exception that they don't receive the experimental treatment (those that do receive it are known as the **experimental group**). For example, in a study testing a weight-loss drug, the control group would be test subjects that don't receive the drug (but they might receive a placebo, such as sugar pill, instead). Look for these various things in the example that follows:

An experiment might be conducted to test the hypothesis that phosphate (a nutrient) promotes the growth of algae in freshwater ponds. A series of artificial ponds are filled with water and half of them are treated by adding phosphate each week, while the other half are treated by adding a non-nutritional mineral that is not used by algae. The experimental variable here is presence/absence of a nutrient (phosphate). One potential controlled variable would be the volume of water in each tank. The amount of water that algae have access to may influence the results, thus researchers want to *control* its influence on the results by making sure all test subjects get the same amount. The control group consists of the tanks that received a placebo (non-nutritional mineral) instead of the phosphate. If the ponds with phosphate show more algal growth, then we have found support for the hypothesis. If they do not, then we reject our hypothesis. Be aware that rejecting one hypothesis does not determine whether or not the other hypotheses can be accepted; it simply eliminates one hypothesis that is not valid (Figure 1.5.3). Using the scientific method, the hypotheses that are inconsistent with experimental data are rejected.

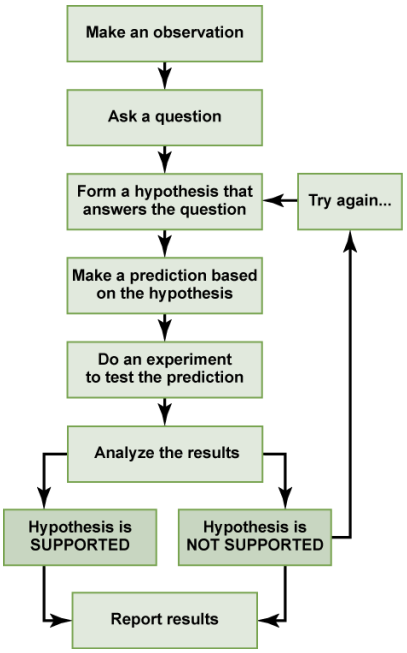


Figure 1.5.4. The scientific method is a series of defined steps that include experiments and careful observation. If a hypothesis is not supported by data, a new hypothesis can be proposed.

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

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

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

Basic and Applied Science

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

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

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

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

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

Another example of the link between basic and applied research is the Human Genome Project, a study in which each human chromosome was analyzed and mapped to determine the precise sequence of the DNA code and the exact location of each gene. (The gene is the basic unit of heredity; an individual's complete collection of genes is his or her genome.) Other organisms have also been studied as part of this project to gain a better understanding of human chromosomes. The Human Genome Project (Figure 1.5.5) relied on basic research carried out with non-human organisms and, later, with the human genome. An important end goal eventually became using the data for applied research seeking cures for genetic diseases.

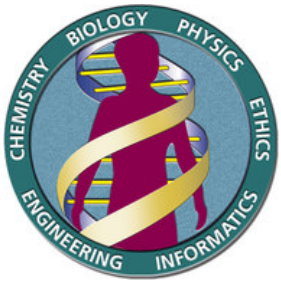


Figure 1.5.5. The Human Genome Project was a 13-year collaborative effort among researchers working in several different fields of science. The project was completed in 2003. (credit: the U.S. Department of Energy Genome Programs)

Scientific Work is Transparent & Open to Critique

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

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

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CHAPTER OVERVIEW

2: Environmental Systems

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2.2: Biological Molecules
2.3: Energy
2.4: The Chemistry of Water
2.5: A Cell is the Smallest Unit of Life
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2.1: The Building Blocks of Molecules

At its most fundamental level, life (and everything else) 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 of one or two letters (such as H, N, O, C, and Na) and possesses unique properties. These unique properties allow elements to combine and bond with each other in specific ways.

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 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.

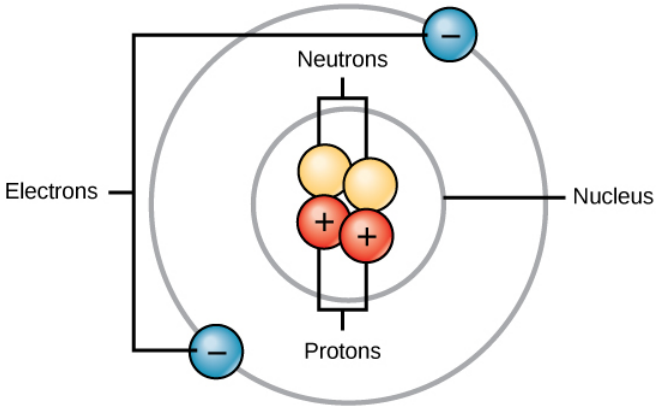


Figure 2.1.1: This element is Helium and has 2 protons (red), two neutrons (yellow), and two electrons (blue). Atoms are made up of protons and neutrons located within the nucleus, and electrons surrounding the nucleus.

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. The number of protons will always equal the number of electrons in an element in its normal state.

Because protons and neutrons each have a mass of 1, the mass of an atom 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 an 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 also 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 into columns (groups) and rows 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.

ART CONNECTION

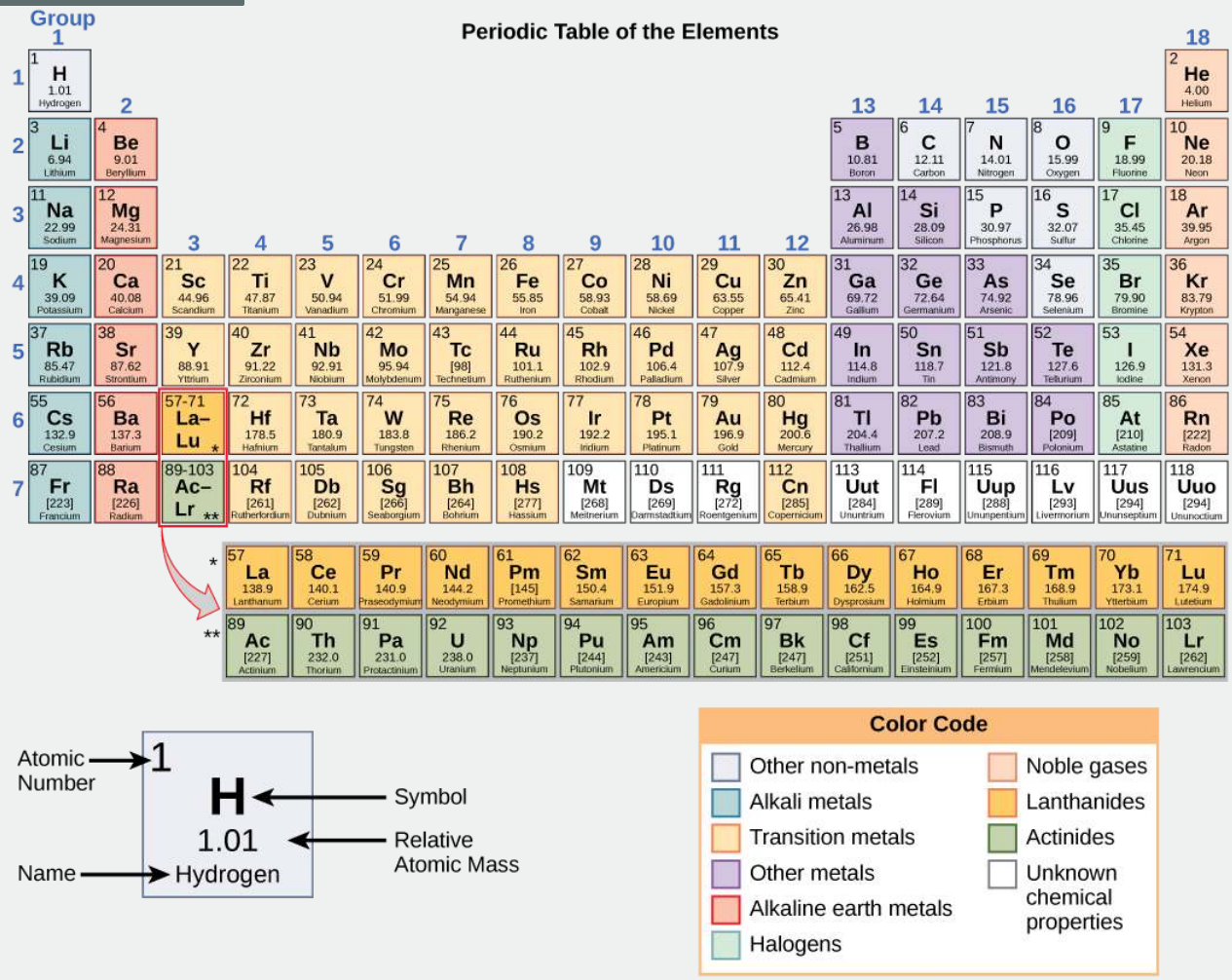


Figure 2.1.2: Arranged in columns and rows based on the characteristics of the elements, the periodic table provides key information about the elements and how they might interact with each other to form molecules. Most periodic tables provide a key or legend to the information they contain.

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

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.

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 try 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, an 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 is easier for sodium to lose that electron and donate that one electron than it is to find and 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 far easier 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 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 are are maximally stable. 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. These would be written with superscript "+1" or "-1": Na^{+1} and Cl^{-1}. If the change is a plus or minus 1, you can also write it as Na^{+} and CL^{-}.

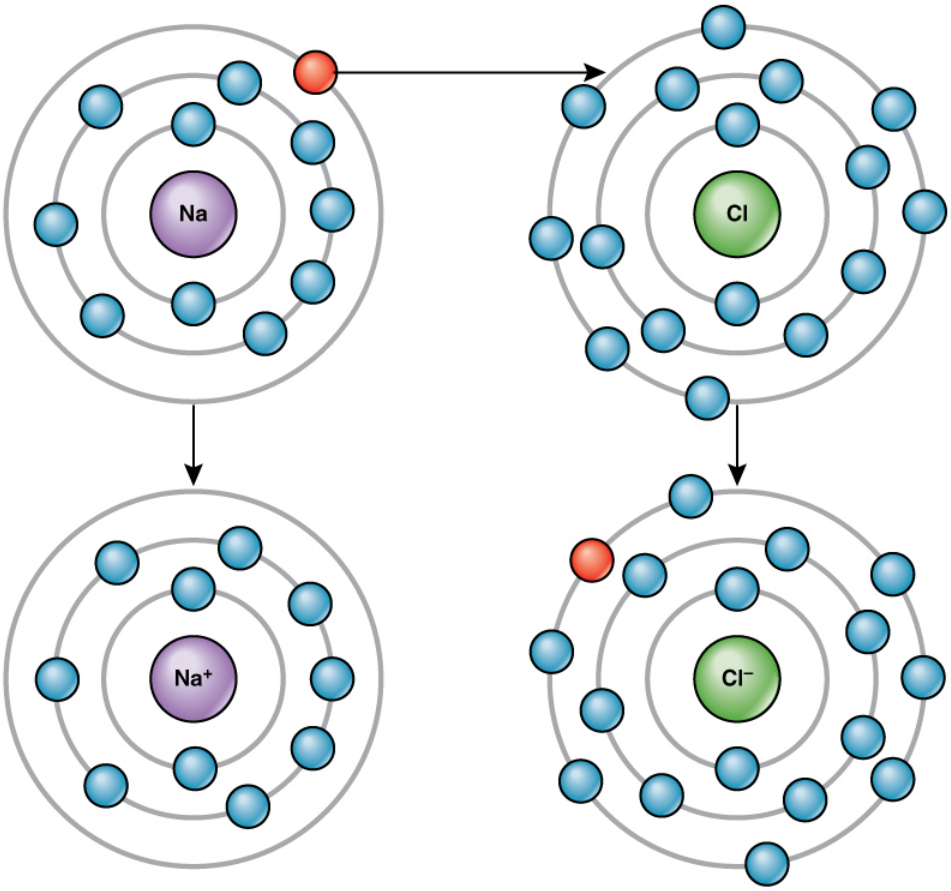


Figure 2.1.4: Elements tend to fill their outermost shells with electrons. To do this, they can either donate or accept electrons from other elements. Once the number of protons and electrons is different, they are called ions and have a positive or negative charge.

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 can stay together and form an ionic bond, or a bond between two oppositely charged 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

The strongest type of 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 bonds) 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 of hydrogen sharing 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 that side a small negative charge, than they spend near the hydrogen nuclei, giving these molecules a small positive charge.

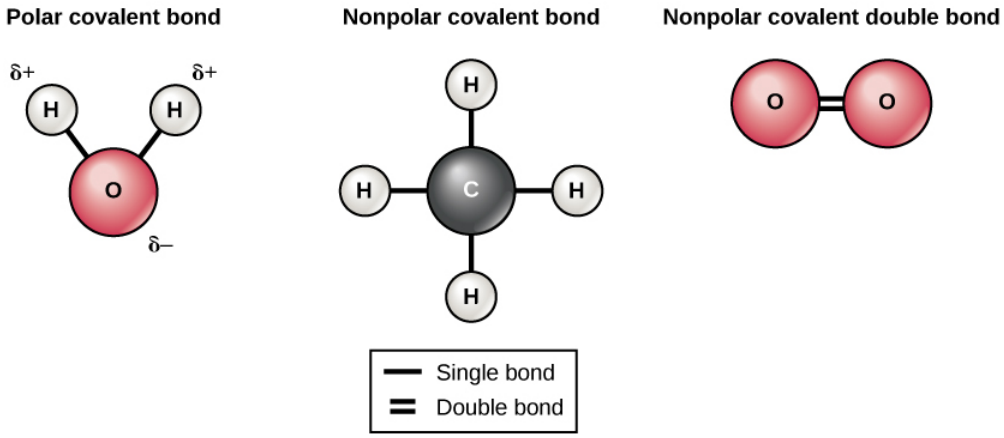


Figure 2.1.5: The water molecule (left) depicts a polar bond with a slightly positive charge on the hydrogen atoms and a slightly negative charge on the oxygen. Examples of nonpolar bonds include methane (middle) and oxygen (right).

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, and just because they are weak doesn't mean they are not important. 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 many unique properties that sustain life. If it were not for hydrogen bonding, water would be a gas rather than a liquid at room temperature.

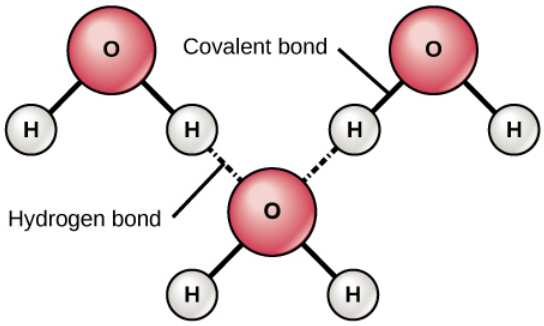


Figure 2.1.6: Hydrogen bonds form between slightly positive (δ+) and slightly negative (δ–) charges of polar covalent molecules, such as water.

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.

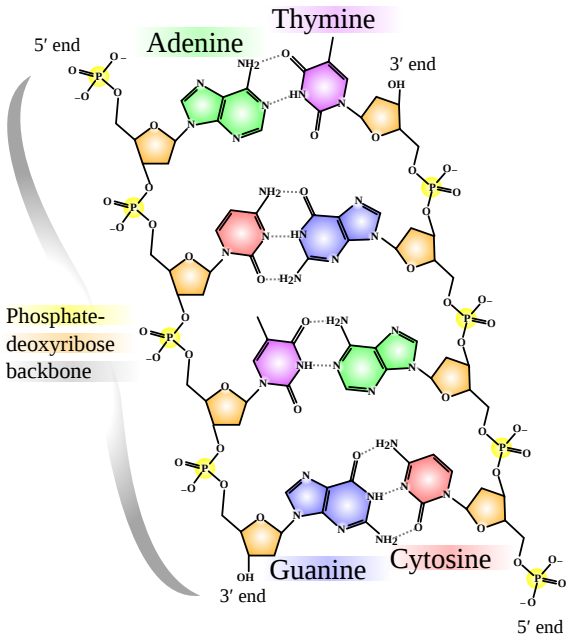


Figure 2.1.7**:** Hydrogen bonds are important in many areas of biology, like holding the two sides of DNA together. The dotted lines shown between the molecules in the center of the DNA image show hydrogen bonds. Madprime (talk · contribs), CC0, via Wikimedia Commons

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, such as allowing geckos to stick to almost any surface.

CAREERS IN ACTION: Radiography Technician

Have you or anyone you know ever had a magnetic resonance imaging (MRI) scan, a mammogram, or an X-ray? These tests produce images of your soft tissues and organs (as with an MRI or mammogram) or your bones (as happens in an X-ray) by

using either radiowaves or special isotopes (radiolabeled or fluorescently labeled) that are ingested or injected into the body. These tests provide data for disease diagnoses by creating images of your organs or skeletal system.

MRI imaging works by subjecting hydrogen nuclei, which are abundant in the water in soft tissues, to fluctuating magnetic fields, which cause them to emit their own magnetic field. This signal is then read by sensors in the machine and interpreted by a computer to form a detailed image.

Some radiography technologists and technicians specialize in computed tomography, MRI, and mammography. They produce films or images of the body that help medical professionals examine and diagnose. Radiologists work directly with patients, explaining machinery, preparing them for exams, and ensuring that their body or body parts are positioned correctly to produce the needed images. Physicians or radiologists then analyze the test results.

Radiography technicians can work in hospitals, doctors' offices, or specialized imaging centers. Training to become a radiography technician happens at hospitals, colleges, and universities that offer certificates, associate's degrees, or bachelor's degrees in radiography.

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.

Art 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.

Glossary

anion
a negative ion formed by gaining electrons

atomic number
the number of protons in an atom

cation
a positive ion formed by losing electrons

chemical bond
an interaction between two or more of the same or different elements that results in the formation of molecules

covalent bond
a type of strong bond between two or more of the same or different elements; forms when electrons are shared between elements

electron
a negatively charged particle that resides outside of the nucleus in the electron orbital; lacks functional mass and has a charge of –1

electron transfer
the movement of electrons from one element to another

element

one of 118 unique substances that cannot be broken down into smaller substances and retain the characteristic of that substance; each element has a specified number of protons and unique properties

hydrogen bond

a weak bond between partially positively charged hydrogen atoms and partially negatively charged elements or molecules

ion

an atom or compound that does not contain equal numbers of protons and electrons, and therefore has a net charge

ionic bond

a chemical bond that forms between ions of opposite charges

isotope

one or more forms of an element that have different numbers of neutrons

mass number

the number of protons plus neutrons in an atom

matter

anything that has mass and occupies space

neutron

a particle with no charge that resides in the nucleus of an atom; has a mass of 1

nonpolar covalent bond

a type of covalent bond that forms between atoms when electrons are shared equally between atoms, resulting in no regions with partial charges as in polar covalent bonds

nucleus

(chemistry) the dense center of an atom made up of protons and (except in the case of a hydrogen atom) neutrons

octet rule

states that the outermost shell of an element with a low atomic number can hold eight electrons

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

polar covalent bond

a type of covalent bond in which electrons are pulled toward one atom and away from another, resulting in slightly positive and slightly negative charged regions of the molecule

proton

a positively charged particle that resides in the nucleus of an atom; has a mass of 1 and a charge of +1

radioactive isotope

an isotope that spontaneously emits particles or energy to form a more stable element

van der Waals interaction

a weak attraction or interaction between molecules caused by slightly positively charged or slightly negatively charged atoms

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2.2: 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 2.2.1).

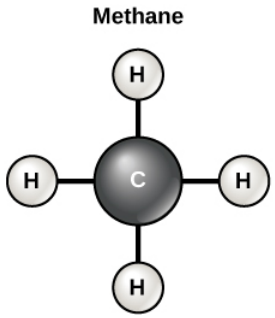
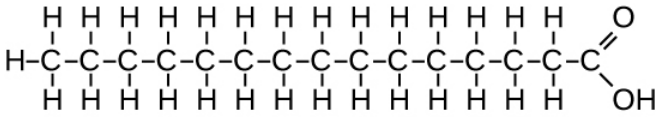
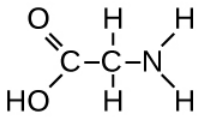


Figure 2.2.1**:** Carbon can form four covalent bonds to create an organic molecule. The simplest carbon molecule is methane (CH_4), depicted here.

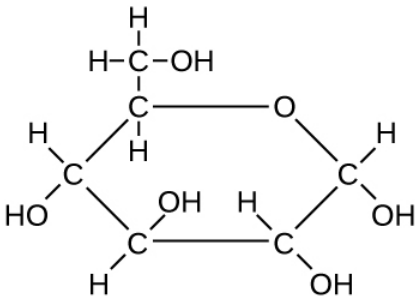
However, structures that are more complex are made using carbon. Any of the hydrogen atoms can be replaced with another carbon atom covalently bonded to the first carbon atom. In this way, long and branching chains of carbon compounds can be made (Figure 2.2.2**a**). The carbon atoms may bond with atoms of other elements, such as nitrogen, oxygen, and phosphorus (Figure 2.2.2**b**). The molecules may also form rings, which themselves can link with other rings (Figure 2.2.2**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.



(a)



(b)



(c)

Figure 2.2.2**:** 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 $(CH_2O)_n$, 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 2.2.3).

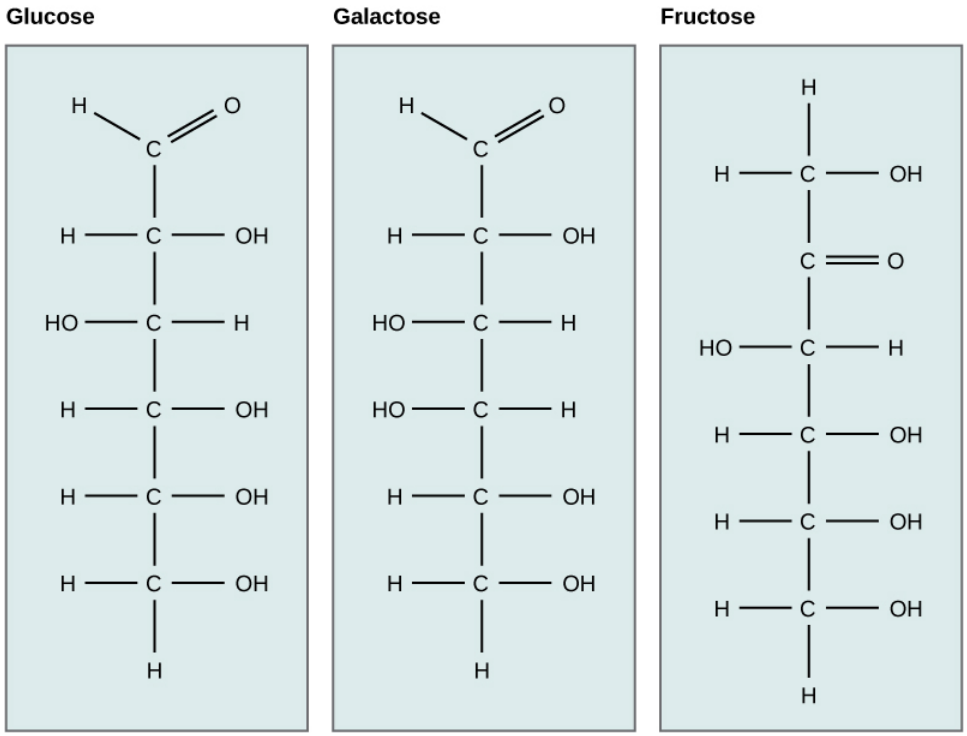


Figure 2.2.3: Glucose, galactose, and fructose are isomeric monosaccharides, meaning that they have the same chemical formula but slightly different structures.

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. It 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. 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. Cellulases 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 2.2.4).

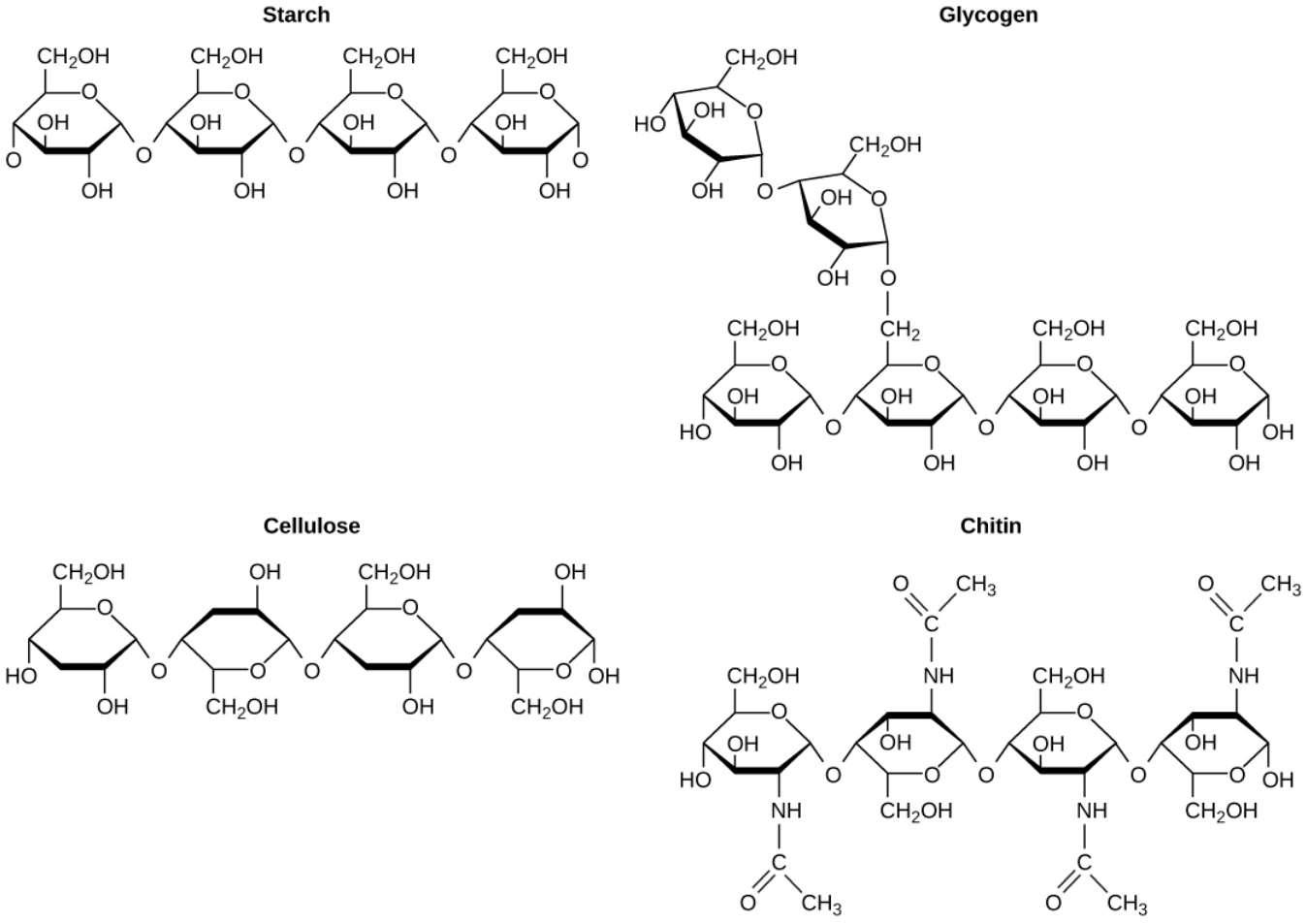


Figure 2.2.4: Although their structures and functions differ, all polysaccharide carbohydrates are made up of monosaccharides and have the chemical formula $(CH_2O)n$.

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 2.2.5). 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 2.2.5: 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 2.2.6).

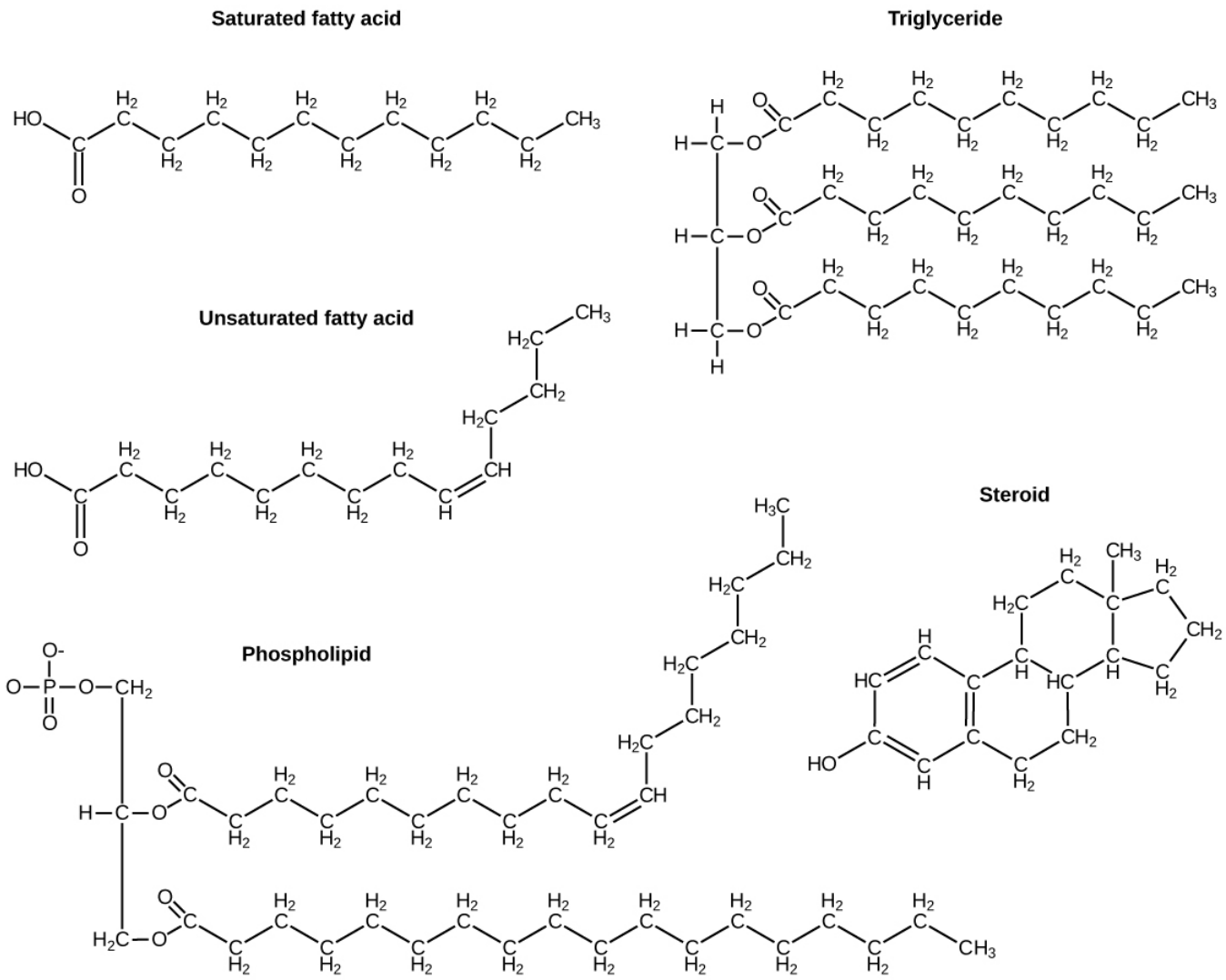


Figure 2.2.6**:** Lipids include fats, such as triglycerides, which are made up of fatty acids and glycerol, phospholipids, and steroids.

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 2.2.7).

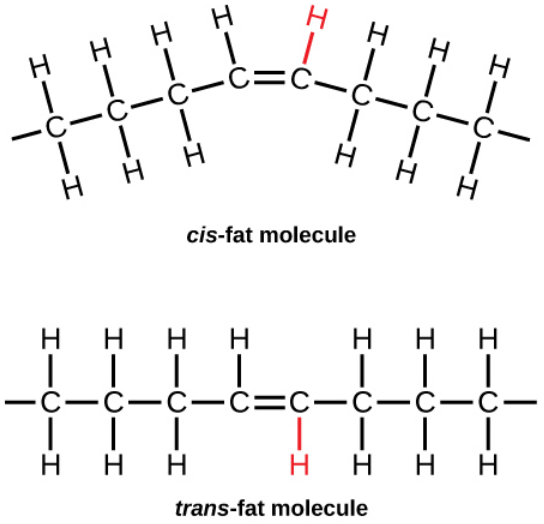


Figure 2.2.7: During the hydrogenation process, the orientation around the double bonds is changed, making a trans-fat from a cis-fat. This changes the chemical properties of the molecule.

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.

CONCEPT IN ACTION

For an additional perspective on lipids, explore “Biomolecules: The Lipids” through this interactive animation.

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 2.2.8).

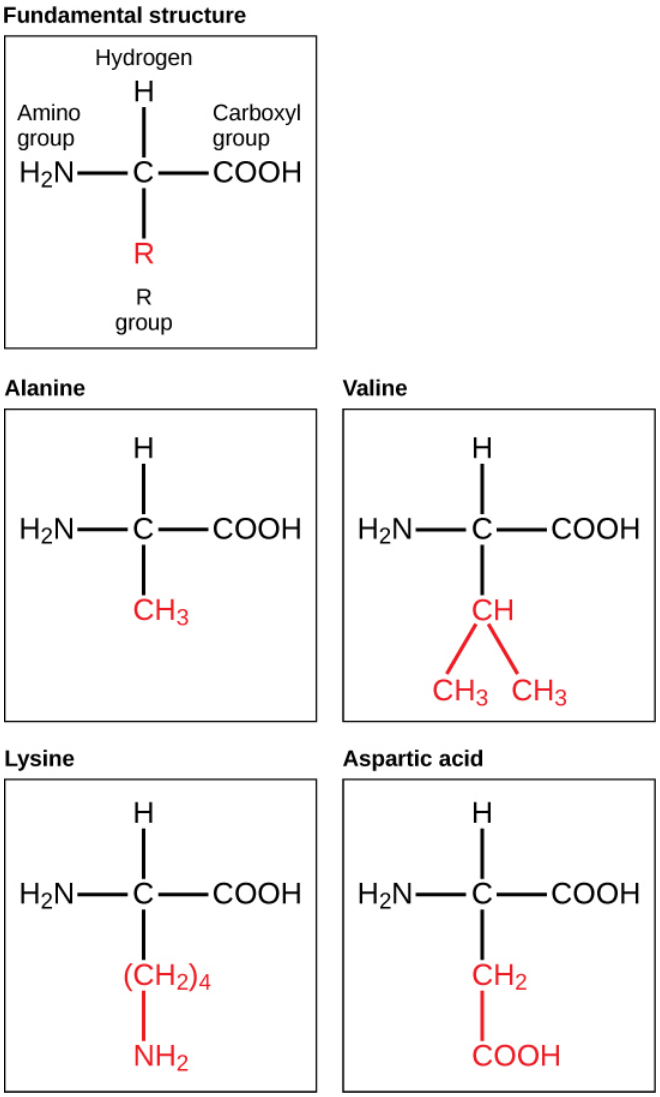


Figure 2.2.8**:** Amino acids are made up of a central carbon bonded to an amino group ($–NH_2$), a carboxyl group (–COOH), and a hydrogen atom. The central carbon's fourth bond varies among the different amino acids, as seen in these examples of alanine, valine, lysine, and aspartic acid.

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 2.2.9).

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.

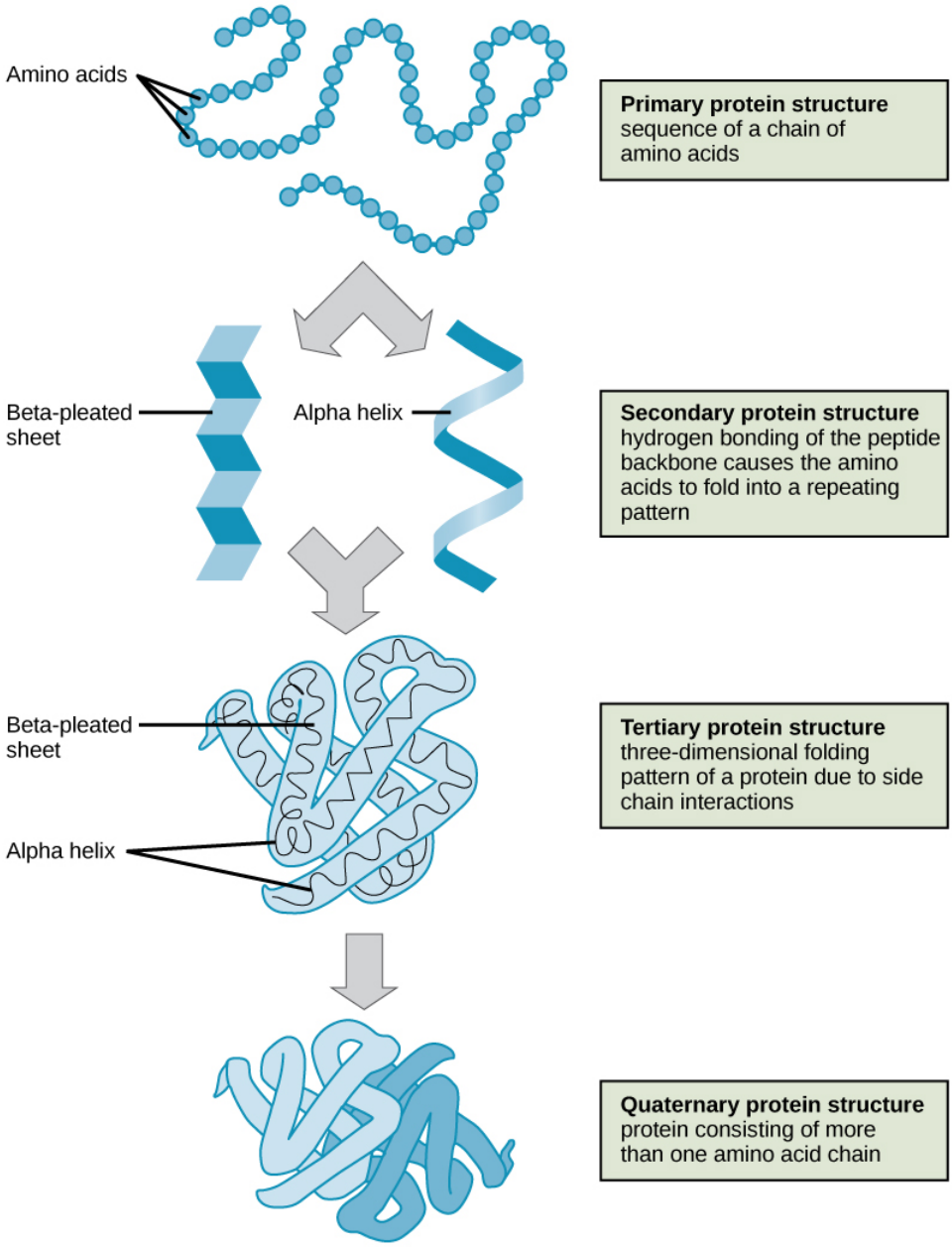


Figure 2.2.9**:** The four levels of protein structure can be observed in these illustrations. (credit: modification of work by National Human Genome Research Institute)

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 temperatures.

CONCEPT IN ACTION

For an additional perspective on proteins, explore “Biomolecules: The Proteins” through this interactive animation.

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 2.2.10). Each nitrogenous base in a nucleotide is attached to a sugar molecule, which is attached to a phosphate group.

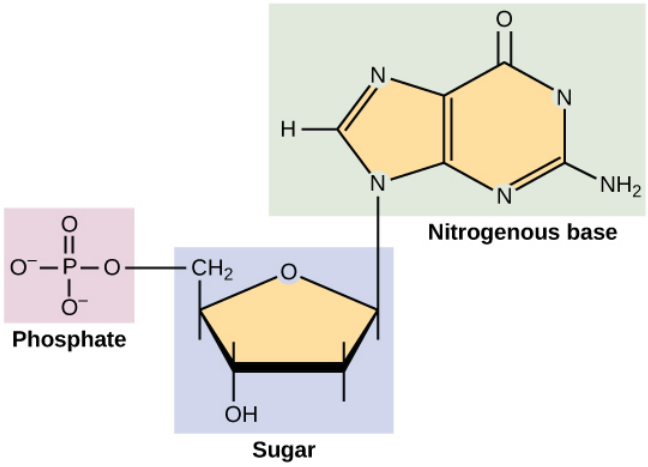


Figure 2.2.10**:** A nucleotide is made up of three components: a nitrogenous base, a pentose sugar, and a phosphate group.

DNA Double-Helical Structure

DNA has a double-helical structure (Figure 2.2.11). 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.

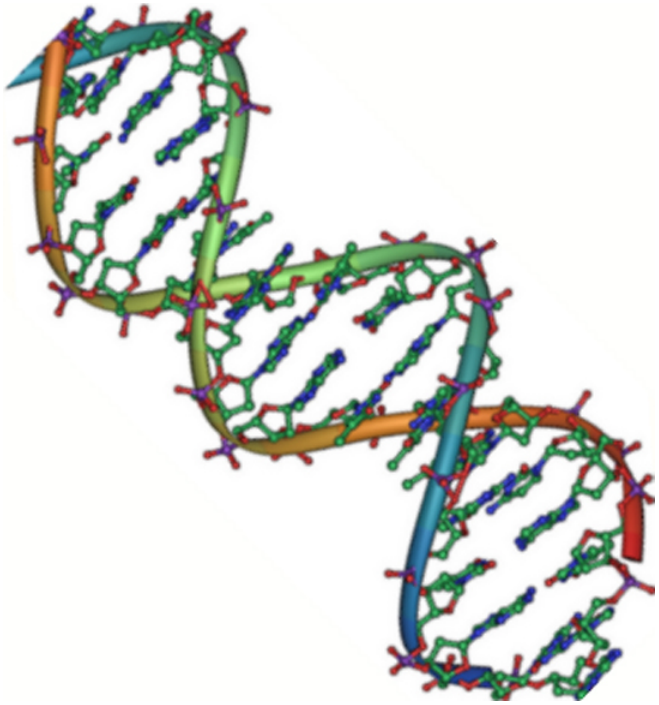


Figure 2.2.11**:** The double-helix model shows DNA as two parallel strands of intertwining molecules. (credit: Jerome Walker, Dennis Myts)

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.

Glossary

amino acid

a monomer of a protein

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

cellulose

a polysaccharide that makes up the cell walls of plants and provides structural support to the cell

chitin

a type of carbohydrate that forms the outer skeleton of arthropods, such as insects and crustaceans, and the cell walls of fungi

denaturation

the loss of shape in a protein as a result of changes in temperature, pH, or exposure to chemicals

deoxyribonucleic acid (DNA)

a double-stranded polymer of nucleotides that carries the hereditary information of the cell

disaccharide

two sugar monomers that are linked together by a peptide bond

enzyme

a catalyst in a biochemical reaction that is usually a complex or conjugated protein

fat

a lipid molecule composed of three fatty acids and a glycerol (triglyceride) that typically exists in a solid form at room temperature

glycogen

a storage carbohydrate in animals

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

lipids

a class of macromolecules that are nonpolar and insoluble in water

macromolecule

a large molecule, often formed by polymerization of smaller monomers

monosaccharide

a single unit or monomer of carbohydrates

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

oil

an unsaturated fat that is a liquid at room temperature

phospholipid

a major constituent of the membranes of cells; composed of two fatty acids and a phosphate group attached to the glycerol backbone

polypeptide
a long chain of amino acids linked by peptide bonds

polysaccharide
a long chain of monosaccharides; may be branched or unbranched

protein
a biological macromolecule composed of one or more chains of amino acids

ribonucleic acid (RNA)
a single-stranded polymer of nucleotides that is involved in protein synthesis

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

starch
a storage carbohydrate in plants

steroid
a type of lipid composed of four fused hydrocarbon rings

***trans*-fat**
a form of unsaturated fat with the hydrogen atoms neighboring the double bond across from each other rather than on the same side of the double bond

triglyceride
a fat molecule; consists of three fatty acids linked to a glycerol molecule

unsaturated fatty acid
a long-chain hydrocarbon that has one or more than one double bonds in the hydrocarbon chain

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2.3: Energy

Virtually every task performed by living organisms requires energy. Nutrients and other molecules are imported into the cell to meet these energy demands. For example, energy is required for the synthesis and breakdown of molecules, as well as the transport of molecules into and out of cells. In addition, processes such as ingesting and breaking down food, exporting wastes and toxins, and movement of the cell all require energy.

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

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

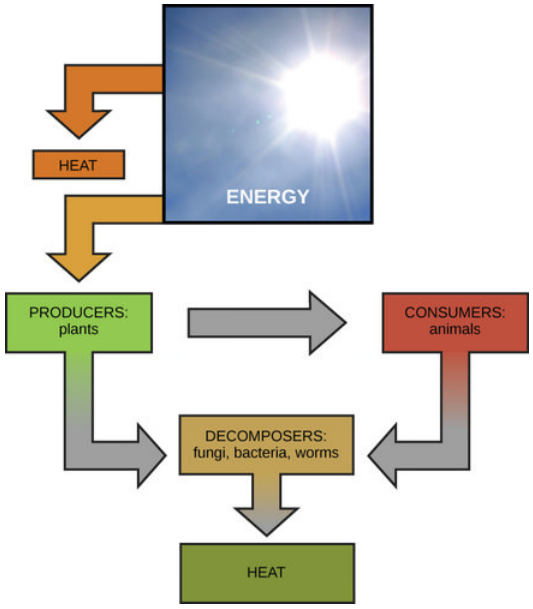


Figure 2.3.1. Ultimately, most life forms get their energy from the sun. Plants use photosynthesis to capture sunlight, and herbivores eat the plants to obtain energy. Carnivores eat the herbivores, and the eventual decomposition of plant and animal material contributes to the nutrient pool.

Energy

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

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

The **first law of thermodynamics** states that the total amount of energy in the universe is constant and conserved. In other words, there has always been and always will be exactly the same amount of energy in the universe. Energy exists in many different forms. According to the first law of thermodynamics, energy may be transferred from place to place or transformed into different forms, but it cannot be created or destroyed. The transfers and transformations of energy take place around us all the time. Light bulbs transform electrical energy into light and heat energy. Gas stoves transform chemical energy from natural gas into heat energy. Plants perform one of the most biologically useful energy transformations on earth: that of converting the energy of sunlight to chemical energy stored within organic molecules (Figure 2.3.2 below).

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

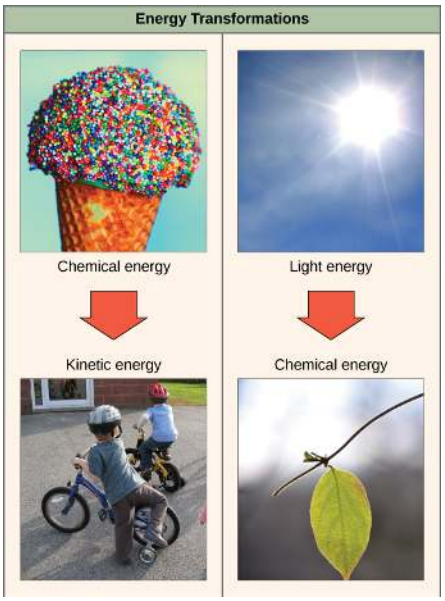


Figure 2.3.2. Shown are some examples of energy transferred and transformed from one system to another and from one form to another. The food we consume provides our cells with the energy required to carry out bodily functions, just as light energy provides plants with the means to create the chemical energy they need. (credit “ice cream”: modification of work by D. Sharon Pruitt; credit “kids”: modification of work by Max from Providence; credit “leaf”: modification of work by Cory Zanker)

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

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

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

Potential and Kinetic Energy

When an object is in motion, there is energy associated with that object. Think of a wrecking ball. Even a slow-moving wrecking ball can do a great deal of damage to other objects. Energy associated with objects in motion is called **kinetic energy**. A speeding bullet, a walking person, and the rapid movement of molecules in the air all have kinetic energy. Now what if that same motionless wrecking ball is lifted two stories above ground with a crane? If the suspended wrecking ball is not moving, is there energy associated with it? The answer is yes. The energy that was required to lift the wrecking ball did not disappear but is now stored in the wrecking ball by virtue of its position and the force of gravity acting on it. This type of energy is called **potential energy**. If the ball were to fall, the potential energy would be transformed into kinetic energy until all of the potential energy was exhausted when the ball rested on the ground. Wrecking balls also swing like a pendulum; through the swing, there is a constant change of potential energy (highest at the top of the swing) to kinetic energy (highest at the bottom of the swing). Other examples of potential energy include the energy of water held behind a dam (Figure 2.3.3 below) or a person about to skydive out of an airplane.



Figure 2.3.3. Still water has potential energy; moving water, such as in a waterfall or a rapidly flowing river, has kinetic energy. (credit “dam”: modification of work by “Pascal”/Flickr; credit “waterfall”: modification of work by Frank Gualtieri)

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

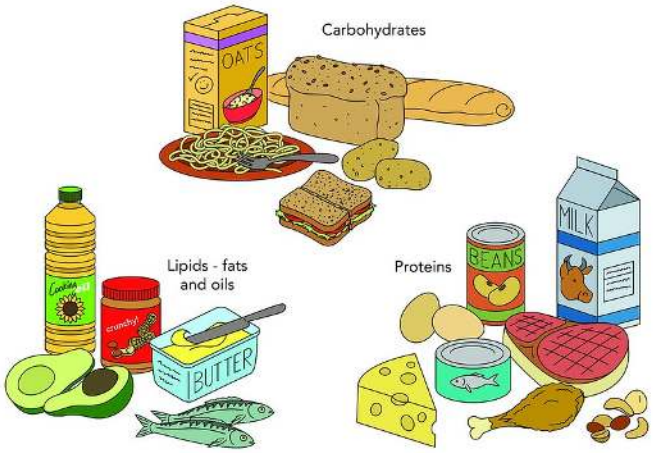


Figure 2.3.4. The energy (calories) found in all food is from the covalent bonds making up the different molecules. “Food groups” by Siyavula Education, CC BY 2.0

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2.4: The Chemistry of 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 2.4.1). These nonpolar compounds are hydrophobic ("water-fearing") and will not dissolve in water.



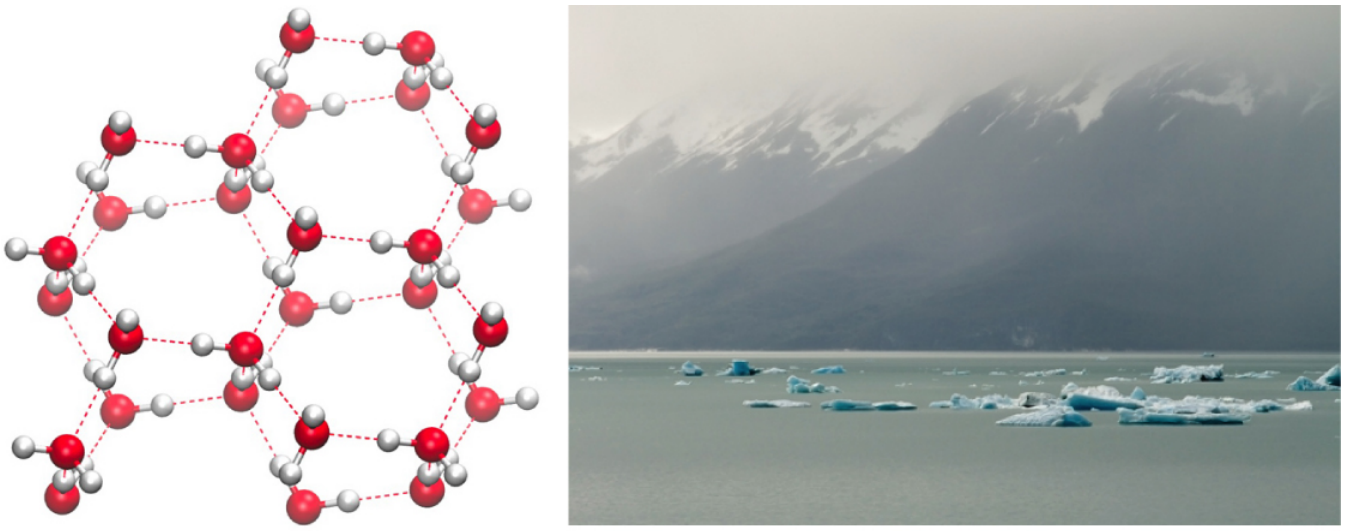
Figure 2.4.1: As this macroscopic image of oil and water show, oil is a nonpolar compound and, hence, will not dissolve in water. Oil and water do not mix. (credit: Gautam Dogra)

Water Stabilizes Temperature

The hydrogen bonds in water allow it to absorb and release heat energy more slowly than many other substances. Temperature is a measure of the motion (kinetic energy) of molecules. As the motion increases, energy is higher and thus temperature is higher. Water absorbs a great deal of energy before its temperature rises. Increased energy disrupts the hydrogen bonds between water molecules. Because these bonds can be created and disrupted rapidly, water absorbs an increase in energy and temperature changes only minimally. This means that water moderates temperature changes within organisms and in their environments. As energy input continues, the balance between hydrogen-bond formation and destruction swings toward the destruction side. More bonds are broken than are formed. 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 2.4.2**a**). 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 2.4.2**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.



(a) (b)

Figure 2.4.2**:** (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

Click here to see 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 2.4.3), 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.

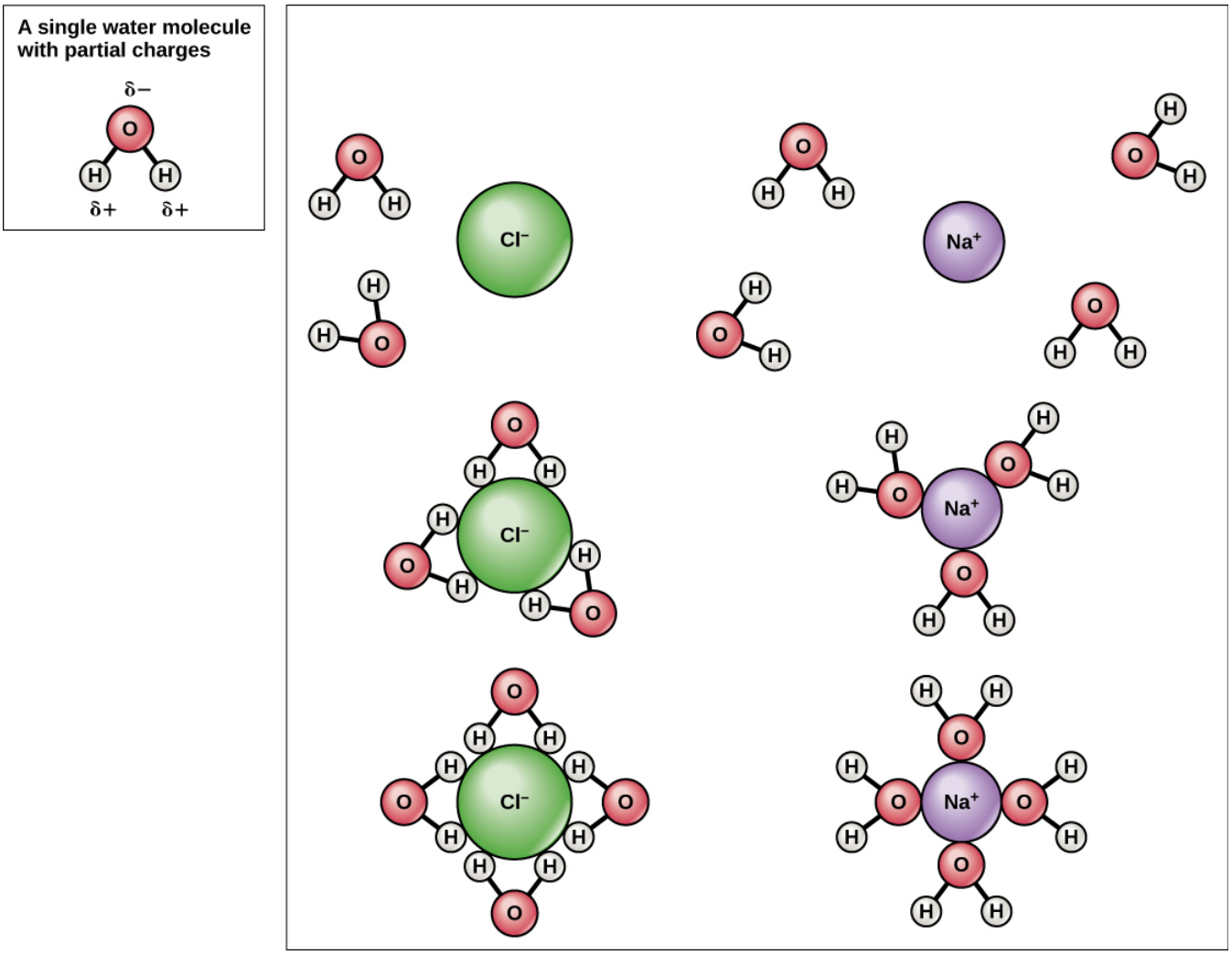


Figure 2.4.3**:** When table salt (NaCl) is mixed in water, spheres of hydration form around the ions.

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 2.4.4).



Figure 2.4.4**:** 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 2.4.5). 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).

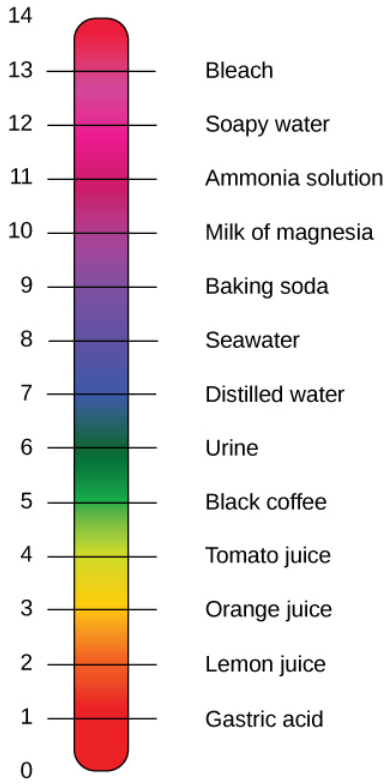


Figure 2.4.5**:** The pH scale measures the amount of hydrogen ions (H^+) in a substance. (credit: modification of work by Edward Stevens)

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. Buffersreadily 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. http://www.ks.uiuc.edu/Research/vmd/

Glossary

acid
a substance that donates hydrogen ions and therefore lowers pH

adhesion
the attraction between water molecules and molecules of a different substance

base
a substance that absorbs hydrogen ions and therefore raises pH

buffer
a solution that resists a change in pH by absorbing or releasing hydrogen or hydroxide ions

cohesion
the intermolecular forces between water molecules caused by the polar nature of water; creates surface tension

evaporation
the release of water molecules from liquid water to form water vapor

hydrophilic
describes a substance that dissolves in water; water-loving

hydrophobic
describes a substance that does not dissolve in water; water-fearing

litmus paper
filter paper that has been treated with a natural water-soluble dye so it can be used as a pH indicator

pH scale
a scale ranging from 0 to 14 that measures the approximate concentration of hydrogen ions of a substance

solvent
a substance capable of dissolving another substance

surface tension
the cohesive force at the surface of a body of liquid that prevents the molecules from separating

temperature
a measure of molecular motion

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2.5: A Cell is the Smallest Unit of Life

Levels of Biological Organization

Living things are highly organized and structured, following a hierarchy of scale from small to large (Figure 2.5.1). The atom is the smallest and most fundamental unit of matter. It consists of a nucleus surrounded by electrons. Atoms combine to form molecules, which are chemical structures consisting of at least two atoms held together by a chemical bond. In plants, animals, and many other types of organisms, molecules come together in specific ways to create structures called organelles. Organelles are small structures that exist within cells and perform specialized functions. As discussed in more detail below, all living things are made of one or more cells.

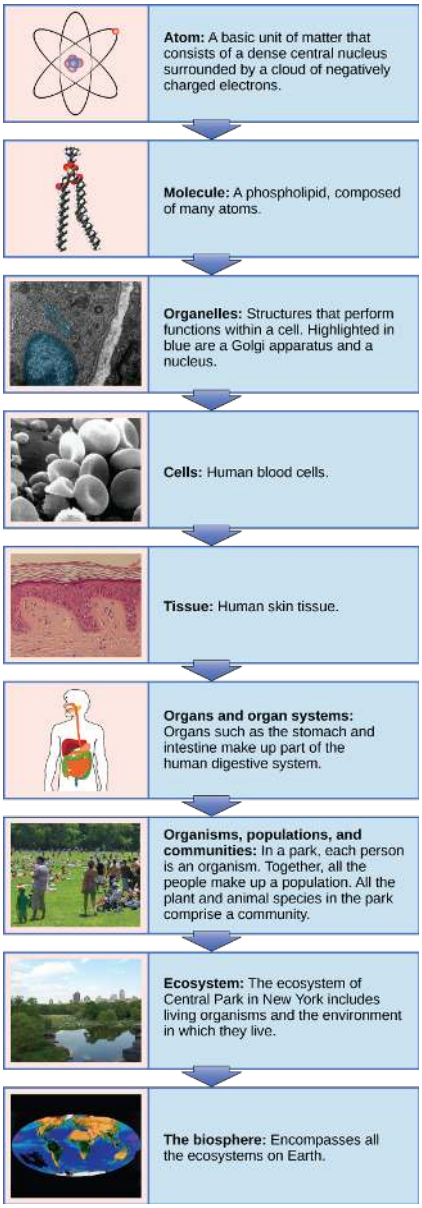


Figure 2.5.1. From an atom to the entire Earth, biology examines all aspects of life. (credit “molecule”: modification of work by Jane Whitney; credit “organelles”: modification of work by Louisa Howard; credit “cells”: modification of work by Bruce Wetzel, Harry Schaefer, National Cancer Institute; 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)

In most multicellular organisms, cells combine to make tissues, which are groups of similar cells carrying out the same function. Organs are collections of tissues grouped together based on a common function. Organs are present not only in animals but also in

plants. An organ system is a higher level of organization that consists of functionally related organs. For example, vertebrate animals have many organ systems, such as the circulatory system that transports blood throughout the body and to and from the lungs; it includes organs such as the heart and blood vessels. Organisms are individual living entities. For example, each tree in a forest is an organism.

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

Cell Theory

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

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

By the late 1830s, botanist Matthias Schleiden and zoologist Theodor Schwann were studying tissues and proposed the unified **cell theory**, which states that all living things are composed of one or more cells, that the cell is the basic unit of life, and that all new cells arise from existing cells. These principles still stand today. There are many types of cells, and all are grouped into one of two broad categories: **prokaryotic** and **eukaryotic**. Animal, plant, fungal, and protist cells are classified as eukaryotic, whereas bacteria and archaea cells are classified as prokaryotic.

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

Components of Prokaryotic Cells

A **prokaryotic cell** is a simple, single-celled (unicellular) organism that lacks a nucleus, or any other membrane-bound organelle. We will shortly come to see that this is significantly different in eukaryotes. Prokaryotic DNA is found in the central part of the cell: a darkened region called the nucleoid (Figure 2.5.2).

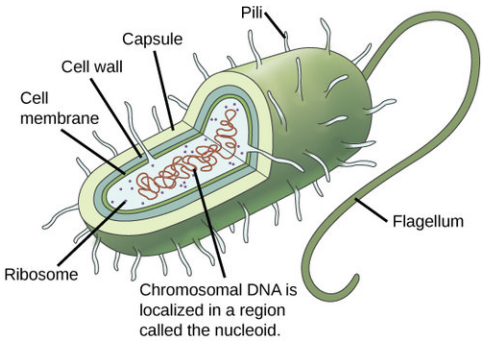


Figure 2.5.2. This figure shows the generalized structure of a prokaryotic cell.

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

Eukaryotic Cells

A **eukaryotic cell** is a cell that has a membrane-bound nucleus and other membrane-bound compartments called **organelles.** There are many different types of organelles, each with a highly specialized function (see Figure 2.5.3). The word eukaryotic means “true kernel” or “true nucleus,” alluding to the presence of the membrane-bound nucleus in these cells. The word “organelle” means “little organ,” and, as already mentioned, organelles have specialized cellular functions, just as the organs of your body have specialized functions.

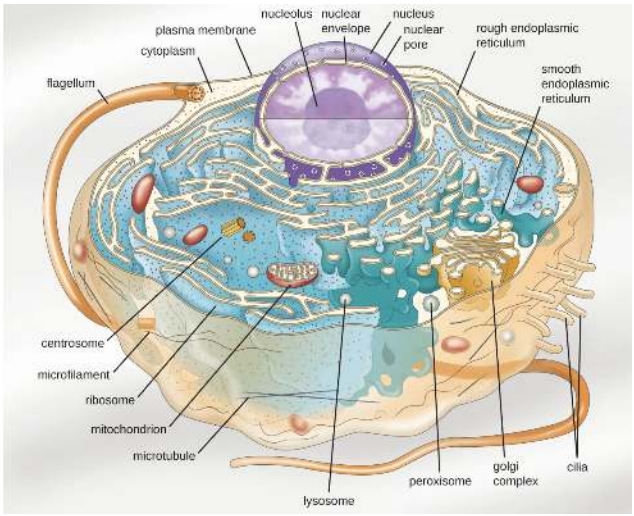


Figure 2.5.3. A eukaryotic cell has many more internal features and organelles than are found in a prokaryotic cell. CNX OpenStax, CC BY 4.0 <https://creativecommons.org/licenses/by/4.0>, via Wikimedia Commons

Cell Size

At 0.1–5.0 µm in diameter, most prokaryotic cells are significantly smaller than eukaryotic cells, which have diameters ranging from 10–100 µm (Figure 2.5.4). The small size of prokaryotes allows ions and organic molecules that enter them to quickly spread to other parts of the cell. Similarly, any waste produced within a prokaryotic cell can quickly move out. However, larger eukaryotic cells have evolved different structural adaptations to enhance cellular transport. Indeed, the large size of these cells would not be possible without these adaptations. In general, cell size is limited because volume increases much more quickly than does cell surface area. As a cell becomes larger, it becomes more and more difficult for the cell to acquire sufficient materials to support the processes inside the cell, because the relative size of the surface area through which materials must be transported declines.

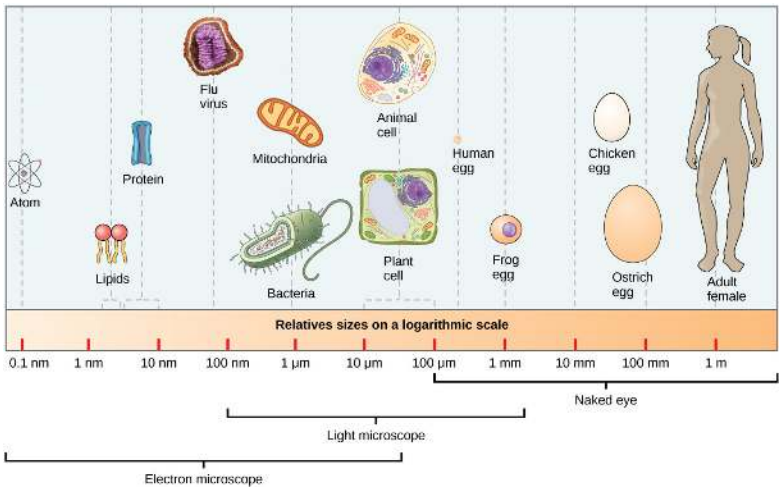


Figure 2.5.4. This figure shows the relative sizes of different kinds of cells and cellular components. An adult human is shown for comparison.

Animal Cells versus Plant Cells

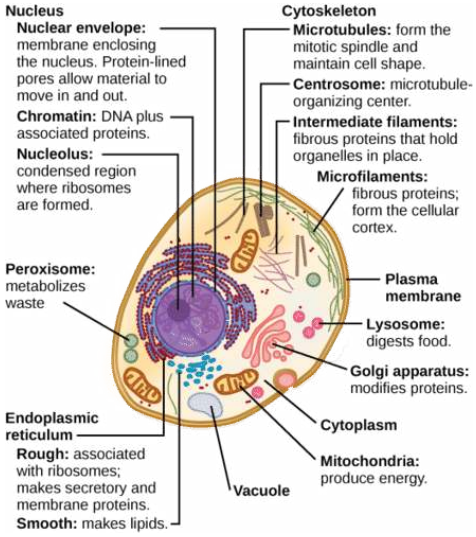


Figure 2.5.5. An example of a typical animal cell.

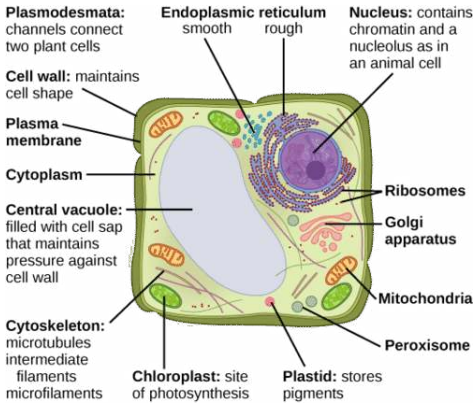


Figure 2.5.6. An example of a typical plant cell.

Despite their fundamental similarities, there are some striking differences between animal and plant cells (Figure 2.5.5). Animal cells have centrioles, centrosomes, and lysosomes, whereas plant cells do not. Plant cells have a rigid cell wall that is external to the plasma membrane, chloroplasts, plasmodesmata, and plastids used for storage, and a large central vacuole, whereas animal cells do not.

Chloroplasts

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

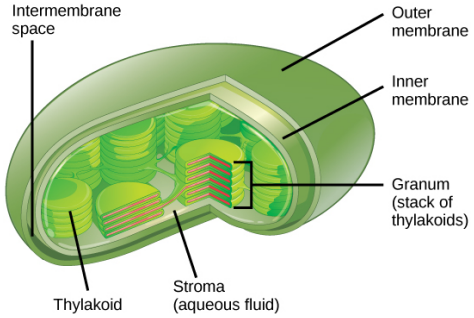


Figure 2.5.7. This simplified diagram of a chloroplast shows its structure.

Chloroplasts have outer and inner membranes, but within the space enclosed by a chloroplast's inner membrane is a set of interconnected and stacked, fluid-filled membrane sacs called thylakoids (Figure 2.5.4 below). Each stack of thylakoids is called a granum (plural = grana). The fluid enclosed by the inner membrane and surrounding the grana is called the stroma. Each structure within the chloroplast has an important function, which is enabled by its particular shape. A common theme in biology is that form and function are interrelated. For example, the membrane-rich stacks of the thylakoids provide ample surface area to embed the proteins and pigments that are vital to photosynthesis.

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2.6: 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 2.6.1. (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 2.6.1). 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 2.6.2. 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 2.6.2). Using this reasoning, all food eaten by humans can be traced back to autotrophs that carry out photosynthesis.

Summary of Photosynthesis

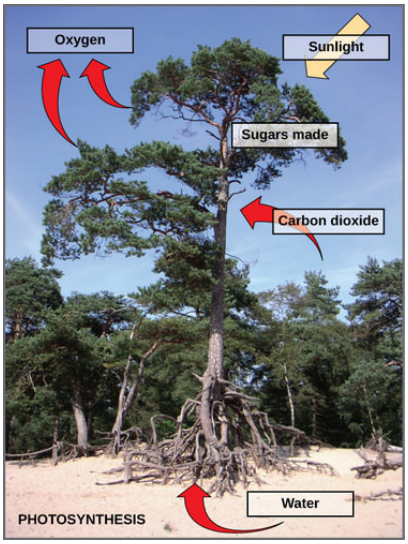


Figure 2.6.3. Photosynthesis uses solar energy, carbon dioxide, and water to release oxygen and to produce energy-storing sugar molecules.

Photosynthesis requires sunlight, carbon dioxide, and water as starting reactants (Figure 2.6.3). 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 2.6.4 below.

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

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

Figure 2.6.4. 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 (see chapter 3.2) needed by complex, multicellular life. Photosynthetic bacteria were likely the first organisms to perform photosynthesis, dating back 2-3 billion years ago. Thanks to their activity, and 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 (see chapter 10.2), which protects life from harmful ultraviolet radiation emitted by the sun. Ozone (O_3) is created from the breakdown and reassembly of O_2.

2. It provides energy for nearly all ecosystems. By transforming light energy into chemical energy, photosynthesis provides the energy used by organisms, whether those organisms are plants, grasshoppers, wolves, or fungi. The only exceptions are found in very rare and isolated ecosystems, such as near deep sea hydrothermal vents where organisms get energy that originally came from minerals, not the sun.
3. It provides the carbon needed for organic molecules. Organisms are primarily made of two things: water and organic molecules, the latter being carbon based. Through the process of **carbon fixation,** photosynthesis takes carbon from CO_2 and converts it into sugars (which are organic). Carbon in these sugars can be re-purposed to create the other types of organic molecules that organisms need, such as lipids, proteins, and nucleic acids. For example, the carbon used to make your DNA was once CO_2 used by photosynthetic organisms (see section 3.1 for more information on food webs).

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2.7: Energy Flow through Ecosystems



Figure 2.7.1. 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 2.7.1).

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 2.7.2).



Figure 2.7.2. 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.

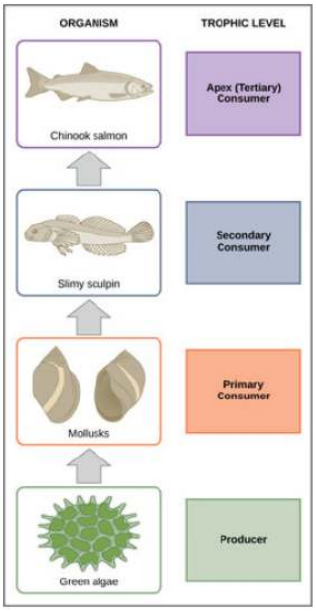


Figure 2.7.3. These are the trophic levels of a food chain in Lake Ontario at the United States–Canada border. Energy and nutrients flow from photosynthetic green algae at the base to the top of the food chain: the Chinook salmon. (credit: modification of work by National Oceanic and Atmospheric Administration/NOAA)

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 2.7.3, 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 2.7.4 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 2.7.5 below).

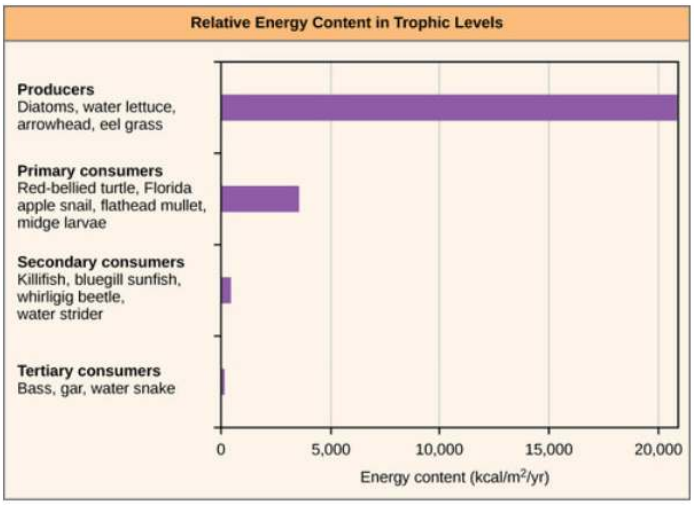


Figure 2.7.4. The relative energy in trophic levels in a Silver Springs, Florida, ecosystem is shown. Each trophic level has less energy available, and usually, but not always, supports a smaller mass of organisms at the next level.

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.

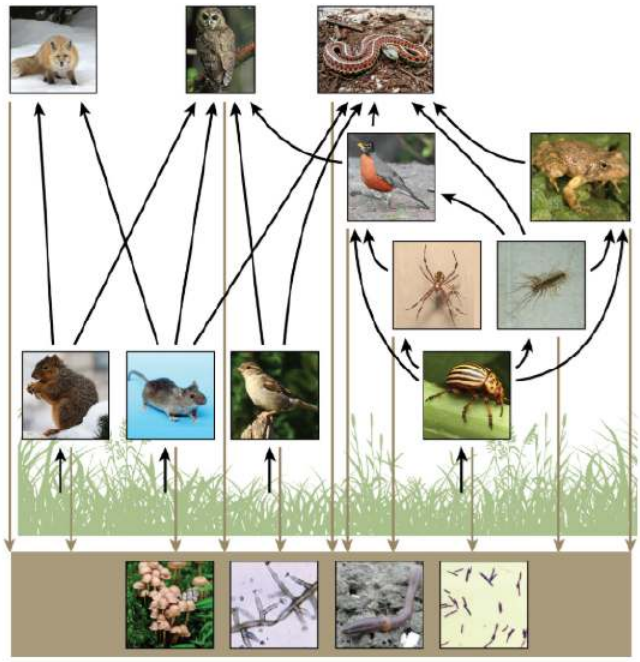


Figure 2.7.5. This food web shows the interactions between organisms across trophic levels. Arrows point from an organism that is consumed to the organism that consumes it. All the producers and consumers eventually become nourishment for the decomposers (fungi, mold, earthworms, and bacteria in the 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**. However, not all of the energy incorporated by producers is available to the other organisms in the food web because producers must also grow and reproduce, which consumes energy. **Net primary productivity** is the energy that remains in the producers after accounting for these organisms’ metabolism and heat loss. The net productivity is then available to the primary consumers at the next trophic level.



Figure 2.7.6. 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 2.7.6). 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.

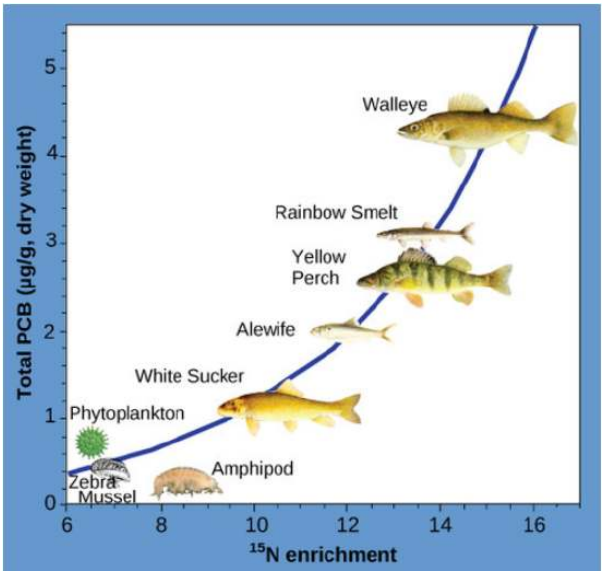


Figure 2.7.7. This chart shows the PCB concentrations found at the various trophic levels in the Saginaw Bay ecosystem of Lake Huron. Notice that the fish in the higher trophic levels accumulate more PCBs than those in lower trophic levels. (credit: Patricia Van Hoof, NOAA)

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 2.7.7 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.

Contributors and Attributions

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2.8: Biogeochemical Cycles- The Water Cycle

Key Points

- Biogeochemical cycles impact the living and non-living world in important interconnected ways.
- Water cycling affects the climate, transports minerals, purifies water and replenishes the land with fresh water.
- Water with a longer residence time, such as water in oceans and glaciers, is not available for short-term cycling, which occurs via evaporation.
- Surface water evaporates (water to water vapor) or sublimates (ice to water vapor), which deposits large amounts of water vapor into the atmosphere.
- Water vapor in the atmosphere condenses into clouds and is eventually followed by precipitation, which returns water to the earth's surface.
- Rain percolates into the ground, where it may evaporate or enter bodies of water.
- Surface runoff enters oceans directly or via streams and lakes.

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 is called **biogeochemical cycles**.

The six elements mentioned 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.

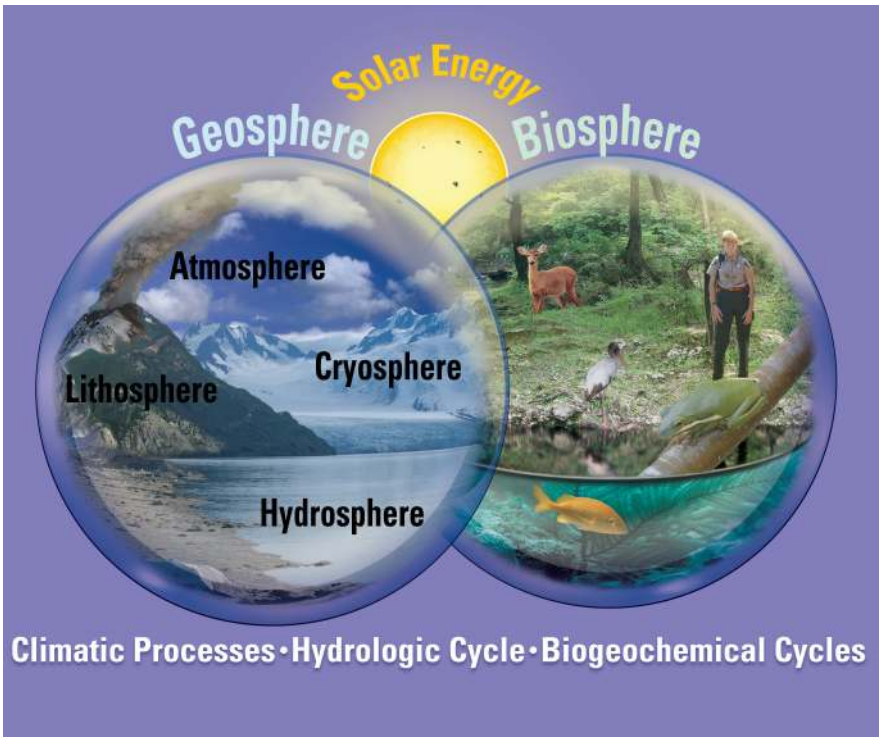


Figure 2.8.1: The recycling of inorganic matter between living organisms and their nonliving environment is called biogeochemical cycles. Image from UCGS.

The Water (Hydrologic) Cycle

Water is essential for all living processes. The human body is more than one-half water and human cells are more than 70 percent water. Thus, most land animals need a supply of fresh water to survive. However, when examining the stores of water on earth, 97.5 percent of it is non-potable salt water (Figure 2.8.1 – 2). Of the remaining water, 99 percent is locked underground as water or as ice but this water is inconveniently located, mostly in Antarctica and Greenland. Shallow groundwater is the largest reservoir of usable fresh water. Less than one percent of fresh water is present in lakes and rivers, the most heavily used water resources. 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.

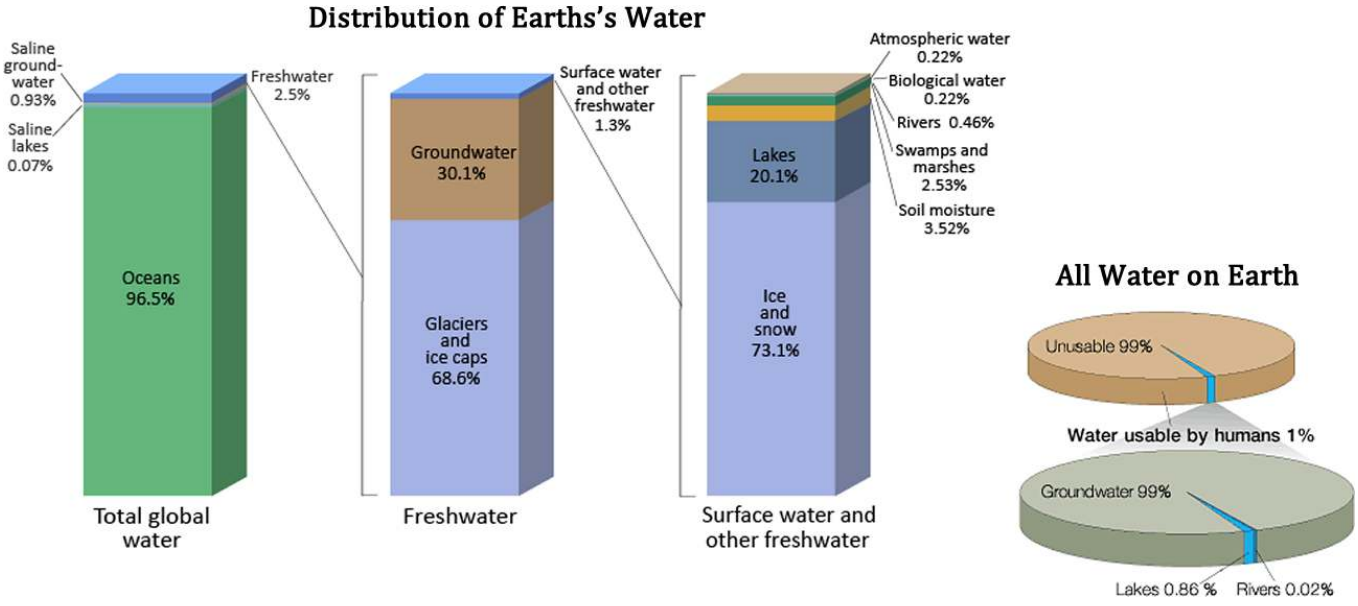


Figure 2.8.2: Earth's Water Reservoirs Bar chart Distribution of Earth's water including total global water, fresh water, and surface water and other fresh water and Pie chart Water usable by humans and sources of usable water. Only 2.5 percent of water on Earth is fresh water, and less than 1 percent of fresh water is easily accessible to living things. *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*

Many living things, such as plants, animals, and fungi, are dependent on the small amount of fresh surface water supply, a lack of which can have massive effects on ecosystem dynamics. 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 is still a major issue in modern times.

Water is the only common substance that occurs naturally on Earth in three forms: solid, liquid and gas. The **hydrosphere** is the area of Earth where water movement and water storage occurs. **Water reservoirs** are the locations where water is stored. (Note that this term can also refer to artificial lakes created by dams.) Water is found as a liquid on the surface (rivers, lakes, oceans) and beneath the surface (groundwater), as ice (polar ice caps and glaciers), and as water vapor in the atmosphere. Figure 2.8.2 illustrates the average time that an individual water molecule may spend in the Earth's major water reservoirs. **Residence time** is a measure of the average time an individual water molecule stays in a particular reservoir.

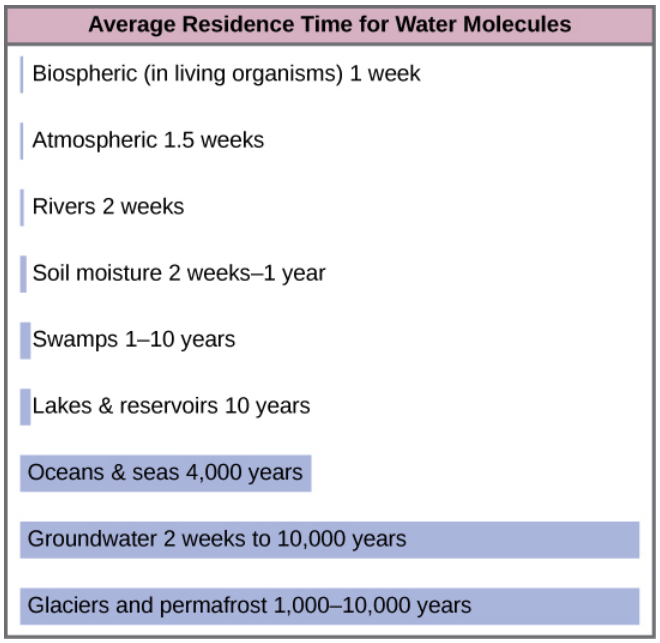


Figure 2.8.3: Average residence time that water remains in each reservoir. Water remains in organisms for about one week, in the atmosphere for 1.5 weeks, in rivers for two weeks, as soil moisture from two weeks to a year, in swamps for 1-10 years, in lakes for 10 years, in oceans and seas for 4,000 years, as groundwater for 2 weeks to 10,000 years, and in glaciers or as permafrost for 1,000-10,000 years. Image from OpenStax (CC-BY).

The Water Cycle

Water cycling is extremely important to ecosystem dynamics as it has a major influence on climate and, thus, on the environments of ecosystems. For example, when water evaporates, it takes up energy from its surroundings, cooling the environment. When it condenses, it releases energy, warming the environment. The evaporation phase of the cycle purifies water, which then replenishes the land with fresh water. The flow of liquid water and ice transports minerals across the globe. It is also involved in reshaping the geological features of the earth through processes including erosion and sedimentation. The various processes that occur during the cycling of water are illustrated in Figure 2.8.4. The processes include the following:

- **evaporation** and **sublimation**
- **transpiration**

- **condensation** and **precipitation**
- subsurface water flow
- surface **runoff** and snowmelt
- streamflow

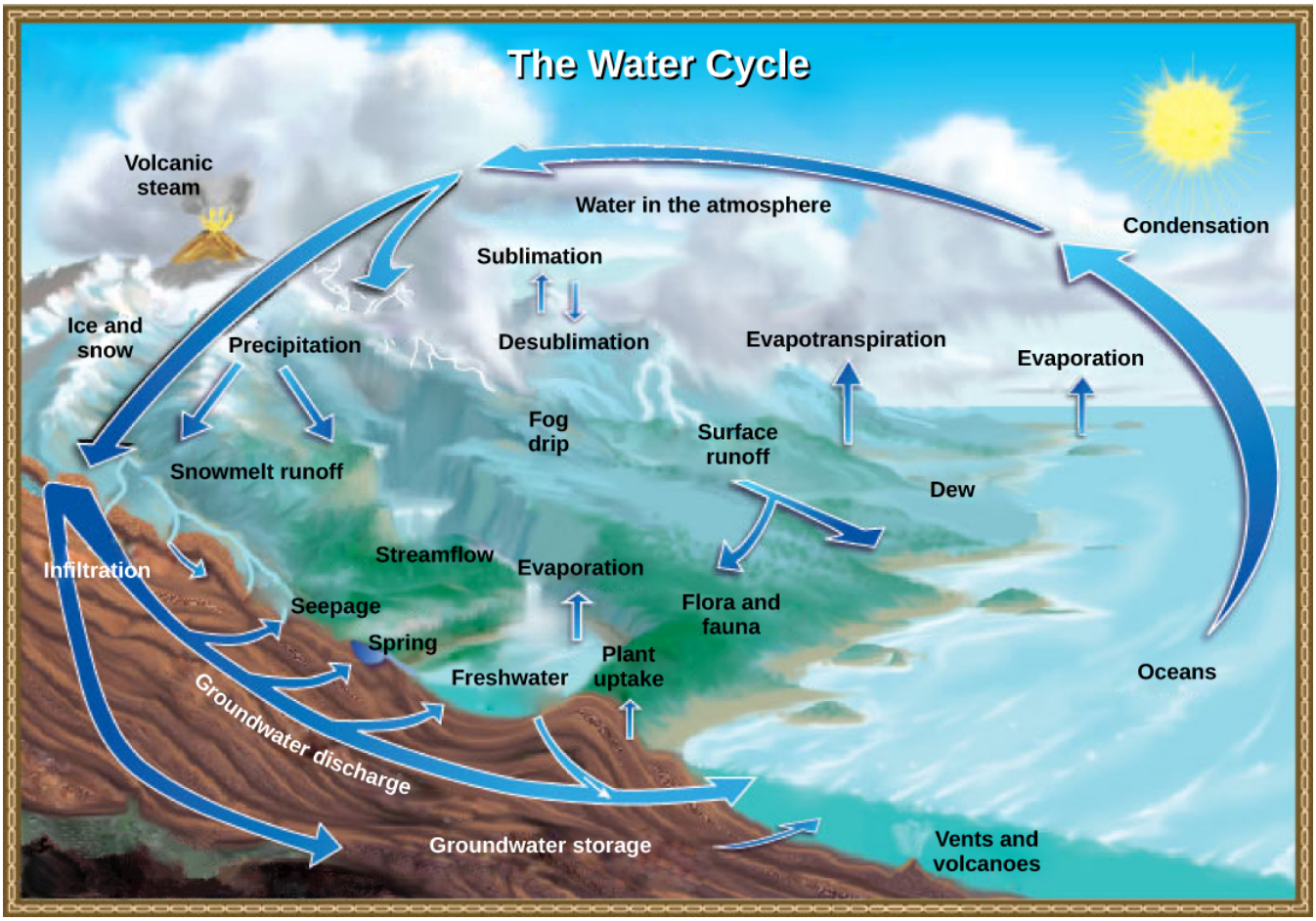


Figure 2.8.4: Water from the land and oceans enters the atmosphere by evaporation or sublimation, where it condenses into clouds and falls as rain or snow. Precipitated water may enter freshwater bodies or infiltrate the soil. The cycle is complete when surface or groundwater reenters the ocean. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

The water cycle is driven by the Sun's energy as it warms the oceans and other surface waters. This leads to evaporation (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. As the water vapor rises in the atmosphere, it cools and condenses. **Condensation** is the process in which water vapor changes to tiny droplets of liquid water. Over time, this water vapor condenses into clouds as liquid or frozen droplets and eventually leads to precipitation (rain or snow), which returns water to Earth's surface. Most precipitation falls into the ocean. Some frozen precipitation becomes part of ice caps and glaciers. These masses of ice can store frozen water for hundreds of years or longer. 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 fresh water either from rain or melting ice. Runoff can make its way through streams and lakes to the oceans or flow directly to the oceans themselves.

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. **Infiltration** is the process through which water sinks into the ground and is determined by the soil or rock type through which water moves. Most water in the soil will 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 **evapotranspiration**. Water enters the

vascular system of the plant through the roots and evaporates, or transpires, through the stomata of the leaves. 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. Here it forms groundwater.

Groundwater is a significant reservoir of fresh water. It exists in the pores between particles in sand and gravel, or in the fissures in rocks. Shallow groundwater flows slowly through these pores and fissures and eventually finds its way to a stream or lake where it becomes a part of the surface water again. Streams do not flow because they are replenished from rainwater directly; they flow because there is a constant inflow from 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 carbon, nitrogen, phosphorus, and sulfur, are cycled from land to water. More precipitation falls near the equator, and landmasses there are characterized by a tropical rainforest climate (Figure 2.8.5). Less precipitation tends to fall near 20–30° 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° 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.

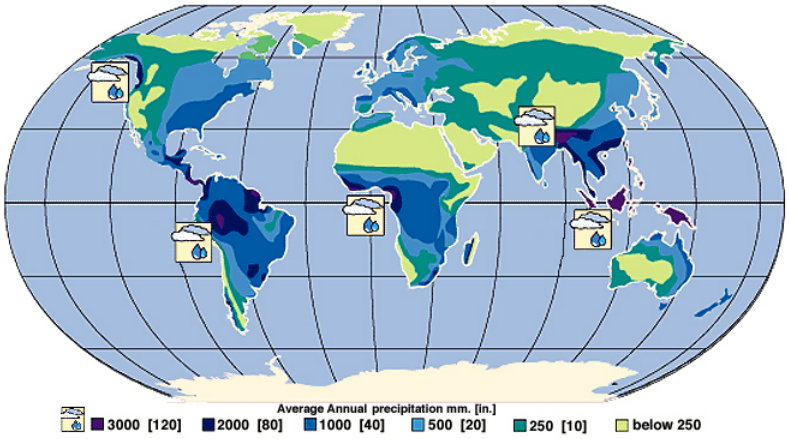
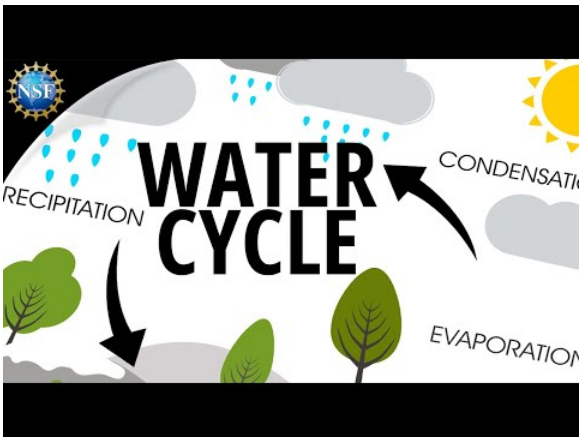


Figure 2.8.5**: World Rainfall Map** The false-color map above shows the amount of rain that falls around the world. Areas of high rainfall include Central and South America, western Africa, and Southeast Asia. Since these areas receive so much rainfall, they are where most of the world's rainforests 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.*

An important part of the water cycle is how water varies in salinity, which is the abundance of dissolved ions in water. The saltwater in the oceans is highly saline, with about 35,000 mg of dissolved ions per liter of seawater. Evaporation is a distillation process 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 forms clouds and sometimes precipitation. After rainwater falls onto land, it dissolves minerals in rock and soil, which increases its salinity. Rain and surface runoff are major ways in which minerals, including phosphorus and sulfur, are cycled from land to water. Freshwater (such as lakes, rivers, and near-surface groundwater) has a relatively low salinity.

The steps of the water cycle are also explained in the video below.





Human Interactions with The Water Cycle

Humans alter the water cycle by extracting large amounts of freshwater from surface waters as well as groundwater. Freshwater supply is one of the most important provisioning ecosystem services on which human well-being depends. By 2000, the rate of our water extraction from rivers and aquifers had risen to almost 4000 cubic kilometers per year. The greatest use of this water is for irrigation in agriculture, but significant quantities of water are also extracted for public and municipal use, as well as industrial applications and power generation.

Other major human interventions in the water cycle involve changes in land cover and infrastructure development of river networks. As we have deforested areas for wood supply and agricultural development we have reduced the amount of vegetation, which naturally acts to trap precipitation as it falls and slow the rate of infiltration into the ground. As a consequence, surface runoff has increased. This, in turn, means flood peaks are greater and erosion is increased. Erosion lowers soil quality and deposits sediment in river channels, where it can block navigation and harm aquatic plants and animals. Where agricultural land is also drained these effects can be magnified. Urbanization also accelerates streamflow by preventing precipitation from filtering into the soil and shunting it into drainage systems.

Additional physical infrastructure has been added to river networks with the aim of altering the volume, timing, and direction of water flows for human benefit. This is achieved with reservoirs, weirs, aqueducts and diversion channels (figure 2.8.6). For example, so much water is removed or redirected from the Colorado River in the western United States that, despite its

considerable size, in some years it is dry before reaching the sea in Mexico. In an extreme example, the Aral Sea in Central Asia has decreased to only 10% of its initial size after water was diverted for agriculture (see this case study for more details).



Figure 2.8.6: The California Aqueduct carries water needed for agriculture from Northern California to Southern California. Image by USGS (public domain).

We also exploit waterways through their use for navigation, recreation, hydroelectricity generation and waste disposal. These activities, especially waste disposal, do not necessarily involve removal of water, but do have impacts on water quality and water flow that have negative consequences for the physical and biological properties of aquatic ecosystems.

The water cycle is key to the ecosystem service of climate regulation as well as being an essential supporting service that impacts the function of all ecosystems. Consider the widespread impacts on diverse natural and human systems when major droughts or floods occur. Consequently, human disruptions of the natural water cycle have many undesirable effects and challenge sustainable development. There are two major concerns. First, the need to balance rising human demand with the need to make our water use sustainable by reversing ecosystem damage from excess removal and pollution of water. Traditionally, considerable emphasis has been on finding and accessing more supply, but the negative environmental impacts of this approach are now appreciated, and improving the efficiency of water use is now a major goal. Second, there is a need for a safe water supply in many parts of the world, which depends on reducing water pollution and improving water treatment facilities.

Although **glaciers** represent the largest reservoir of fresh water, they generally are not used as a water source because they are located too far from most people (Figure 2.8.7). Melting glaciers do provide a natural source of river water and groundwater. During the last Ice Age there was as much as 50% more water in glaciers than there is today, which caused sea level to be about 100 m lower. Over the past century, sea level has been rising in part due to melting glaciers. If Earth's climate continues to warm, the melting glaciers will cause an additional rise in sea level.



Figure 2.8.7: Figure 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

Further "Reading"

For more information on the water cycle you might want to watch this water cycle video from USGS.

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2.9: Carbon Cycle

Key Points

- Carbon is present in all organic molecules; carbon compounds contain large amounts of energy, which humans use as fuel.
- The biological carbon cycle is the rapid exchange of carbon among living things; autotrophs use carbon dioxide produced by heterotrophs to produce glucose and oxygen, which are then utilized by heterotrophs.
- The biogeochemical cycle occurs at a much slower rate than the biological cycle since carbon is stored in carbon reservoirs for long periods of time.
- Carbon dioxide from the atmosphere dissolves in water, combining with water molecules to form carbonic acid, which then ionizes to carbonate and bicarbonate ions.
- Most of the carbon in the ocean is in the form of bicarbonate ions, which can combine with seawater calcium to form calcium carbonate ($CaCO3$), a major component of marine organism shells.
- Carbon can enter the soil as a result of the decomposition of living organisms, the weathering of rocks, the eruption of volcanoes, and other geothermal systems.

The Carbon Cycle

Carbon is the fourth most abundant element in living organisms. Carbon is present in all organic molecules, and its role in the structure of macromolecules is of primary importance to living organisms. Carbon compounds contain energy, and many of these compounds from plants and algae have remained stored as fossilized carbon, which humans use as fuel. Since the 1800s, the use of fossil fuels has accelerated. As global demand for Earth’s limited fossil fuel supplies has risen since the beginning of the Industrial Revolution, the amount of carbon dioxide in our atmosphere has increased as the fuels are burned. This increase in carbon dioxide has been 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 2.9.1. The overall effect is that carbon is constantly recycled in the dynamic processes taking place in the atmosphere, at the surface and in the crust of the earth. The vast majority of carbon resides as inorganic minerals in crustal rocks. Other **reservoirs** of carbon, places where carbon accumulates, include the oceans and atmosphere. Some of the carbon atoms in your body today may long ago have resided in a dinosaur's body, or perhaps were once buried deep in the Earth's crust as carbonate rock minerals.

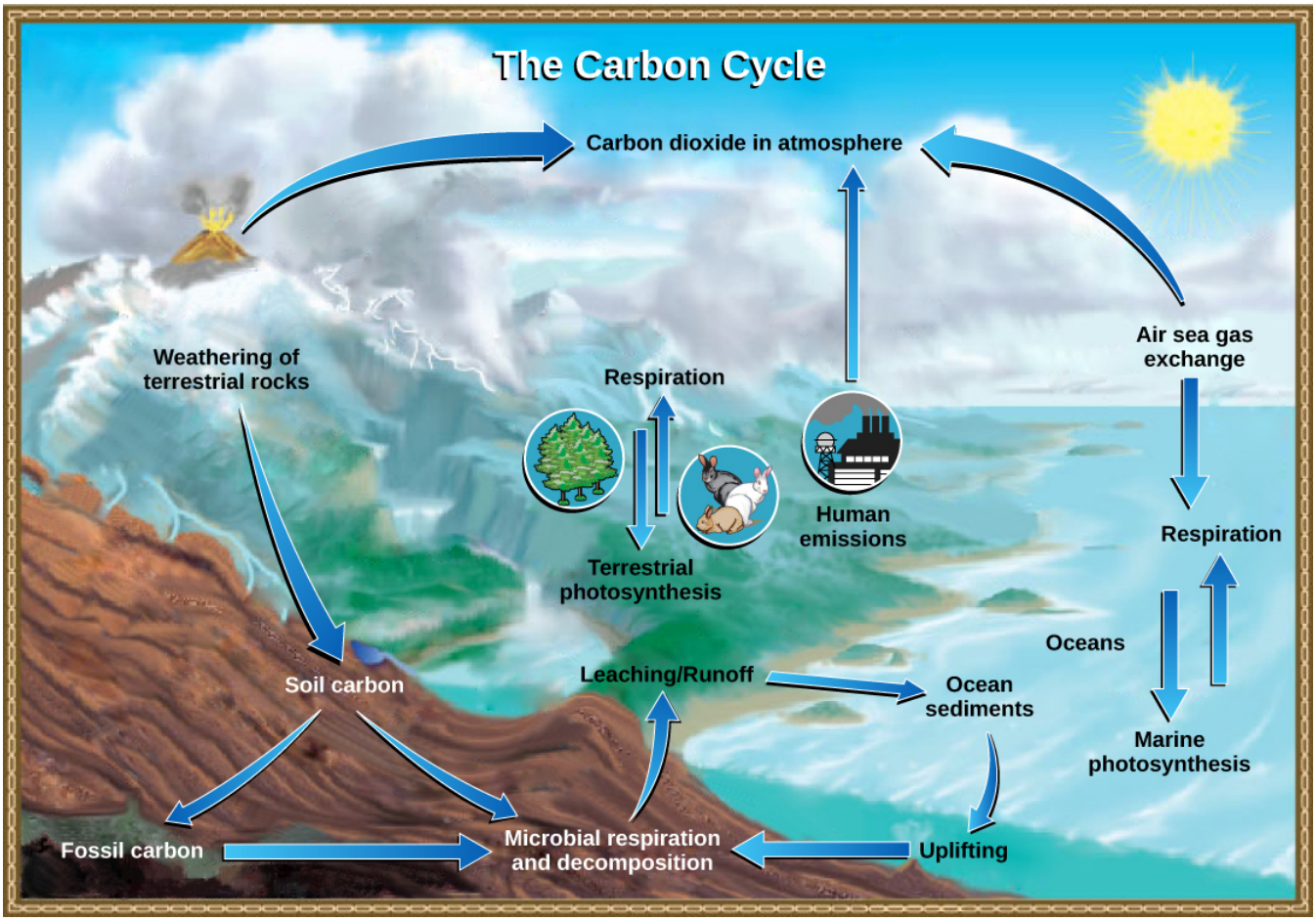


Figure 2.9.1: Carbon dioxide gas exists in the atmosphere and is dissolved in water. Photosynthesis converts carbon dioxide gas to organic carbon, and respiration cycles the organic carbon back into carbon dioxide gas. Long-term storage of organic carbon occurs when matter from living organisms is buried 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)

Carbon Cycles Quickly between Organisms and the Atmosphere

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 other organic molecules like complex carbohydrates (such as starch), proteins and lipids. 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.



(a) (b) (c)

Figure 2.9.2: (a) Plants, (b) algae, and (c) certain bacteria, called cyanobacteria, are 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 2.9.2). Oceanic algae contribute enormous quantities of food and oxygen to global food chains. Carbon dioxide is the basic building block that most autotrophs use to build multi-carbon, high-energy compounds, such as glucose. Most terrestrial autotrophs obtain their carbon dioxide directly from the atmosphere, while marine autotrophs acquire it in the dissolved form (bicarbonate, HCO_3^-).

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. Heterotrophs acquire the high-energy carbon compounds from the autotrophs by consuming them and breaking them down by respiration to obtain cellular energy, such as ATP. The most efficient type of respiration, aerobic respiration, requires oxygen obtained from the atmosphere or dissolved in water. Thus, there is a constant exchange of oxygen and carbon dioxide between the autotrophs (which need the carbon) and the heterotrophs (which need the oxygen). Humans are heterotrophs, as are all animals and fungi. A deer obtains energy by eating plants. A wolf eating a deer obtains energy that originally came from the plants eaten by that deer (Figure 2.9.3). Using this reasoning, all food eaten by humans can be traced back to autotrophs that carry out photosynthesis.



Figure 2.9.3: 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)

Plants, animals, and other organisms break down organic molecules during the process of **aerobic cellular respiration**, which consumes oxygen and releases energy, water and carbon dioxide. Carbon dioxide is returned to the atmosphere during gaseous exchange. Another process by which organic material is recycled is the decomposition of dead organisms. During this process,

bacteria and fungi break down the complex organic compounds. Decomposers may do respiration, releasing carbon dioxide, or other processes that release methane (CH_4).

Photosynthesis and respiration are actually reciprocal to one another with regard to the cycling of carbon: photosynthesis removes carbon dioxide from the atmosphere and respiration returns it (Figure 2.9.4). A significant disruption of one process can therefore affect the amount of carbon dioxide in the atmosphere.

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

Figure 2.9.4: This equation means that six molecules of carbon dioxide (CO_2) combine with six molecules of water (H_2O) in the presence of sunlight. This produces one molecule of glucose ($C_6H_{12}O_6$) and six molecules of oxygen (O_2).

Cellular respiration is only one process that releases carbon dioxide. Physical processes, such as the eruption of volcanoes and release from **hydrothermal vents** (openings in the ocean floor) add carbon dioxide to the atmosphere. Additionally, the **combustion** of wood and fossil fuels releases carbon dioxide. 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 Cycles Slowly between Land and the Ocean

The movement of carbon through land, water, and air is complex, and, in many cases, it occurs much more slowly geologically than the movement between living 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, and each one affects the other reciprocally. Atmospheric carbon dioxide also dissolves in the ocean, reacting with water molecules to form carbonic acid and then dissociating into bicarbonate (HCO_3^-) and carbonate ions (CO_3^{2-}). More than 90 percent of the carbon in the ocean is found as bicarbonate ions. 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 form sediments on the ocean floor. Over geologic time, the calcium carbonate forms limestone, which comprises the largest carbon reservoir on Earth.

Step 1: CO_2 (atmospheric) ⇌ CO_2 (dissolved)
Step 2: CO_2 (dissolved) + H_2O ⇌ H_2CO_3 (carbonic acid)
Step 3: H_2CO_3 ⇌ + H^+ + HCO_3^- (biocarbonate ion)
Step 4: HCO_3^- ⇌ H^+ + CO_3^{2-} (carbonate ion)

Figure 2.9.1: **Formation of bicarbonate**: Carbon dioxide reacts with water to form bicarbonate and carbonate ions.

On land, carbon is stored in soil as organic carbon as a result of the decomposition of living organisms or from **weathering** of terrestrial rock and minerals. This carbon can be leached into the water reservoirs by surface runoff. Partially decomposed plants and algae are sometimes buried and compressed between layers of sediments. After millions of years fossil fuels such as coal, oil, and natural gas are formed. 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. The ocean sediments are subducted by the actions of **plate**

tectonics, melted and then returned to the surface during volcanic activity. Carbon is released as carbon dioxide when a volcano erupts or from volcanic hydrothermal vents.Plate tectonics can also cause **uplifting**, returning ocean sediments to land.

Importance of the Carbon Cycle

The carbon cycle is crucially important to the biosphere. If not for the recycling processes, carbon might long ago have become completely sequestered in crustal rocks and sediments, and life would no longer exist (Figure 2.9.5). Photosynthesis not only makes energy and carbon available to higher trophic levels, but it also releases gaseous oxygen (O_2). Gaseous oxygen is necessary for cellular respiration to occur. 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.



Figure 2.9.5: Decomposers will break down the organic compounds in this fallen tree at Cliffs of the Neuse State Park in Wayne County, North Carolina, releasing carbon dioxide into the atmosphere. Decomposition ensures that carbon dioxide will be available in the atmosphere for photosynthetic organisms, which then provide carbon for consumers. Image by Gerry Dincher (CC-BY-SA).

The global carbon cycle contributes substantially to the provisioning ecosystem services upon which humans depend. We harvest approximately 25% of the total plant biomass that is produced each year on the land surface to supply food, fuel wood and fiber from croplands, pastures and forests. In addition, the global carbon cycle plays a key role in regulating ecosystem services because it significantly influences climate via its effects on atmospheric CO_2 concentrations.

Human Alteration of the Carbon Cycle

Atmospheric CO_2 concentration increased from 280 parts per million (ppm) to 413 ppm between the start of industrial revolution in the late eighteenth century and 2020. This reflected a new flux in the global carbon cycle—anthropogenic CO_2 emissions—where humans release CO_2 into the atmosphere by burning fossil fuels and changing land use. Fossil fuel burning takes carbon from coal, gas, and oil reserves, where it would be otherwise stored on very long time scales, and introduces it into the active carbon cycle. Land use change releases carbon from soil and plant biomass pools into the atmosphere, particularly through the process of deforestation for wood extraction or conversion of land to agriculture. Carbon dioxide is also added to the atmosphere by the breeding and raising of livestock. In 2018, the additional flux of carbon into the atmosphere from anthropogenic sources was estimated to be 36.6 gigatons of carbon (GtC = 1 billion tons of carbon)—a significant disturbance to the natural carbon cycle that had been in balance for several thousand years previously. High levels of carbon dioxide in the atmosphere cause warming that results in climate change.

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2.10: Nitrogen Cycle

Key Points

- Bacteria, such as cyanobacteria, convert nitrogen into nitrogen gas via nitrogen fixation.
- Nitrogen fixation occurs in three steps: ammonification, nitrification, and denitrification.
- Human activity can release nitrogen into the environment by the combustion of fossil fuels and by the use of artificial fertilizers in agriculture.
- Atmospheric nitrogen is responsible for acid rain, the release of greenhouse gasses, and eutrophication.
- Nitrogen fixation can be performed by marine bacteria; nitrogen falls to the ocean floor as sediment and is then moved to land, becoming incorporated into terrestrial rock.

The Nitrogen Cycle

All organisms require nitrogen because it is an important component of nucleic acids, proteins, and other organic molecules. Getting nitrogen into the living world is difficult. Plants and phytoplankton are not equipped to incorporate nitrogen from the atmosphere (which exists as tightly bonded, triple covalent N_2) even though this molecule comprises approximately 78 percent of the atmosphere (Figure 2.10.1). Nitrogen enters the living world through **nitrogen fixation (**Figure $2.10.1-2$, the process of converting nitrogen gas into ammonia (NH_3), which spontaneously becomes ammonium (NH_4^+). Ammonium is found in bodies of water and in the soil (figure $2.10.1-2$).

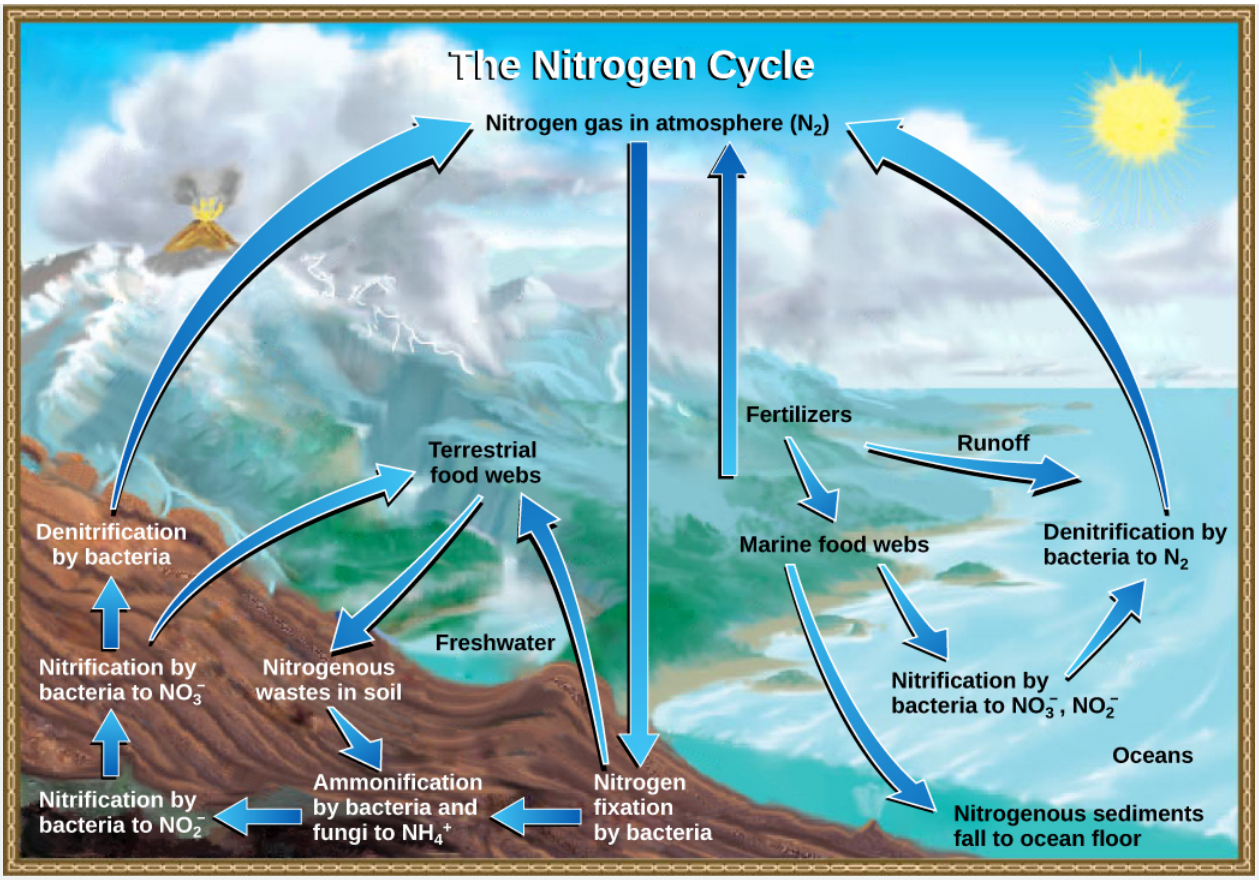


Figure 2.10.1: Nitrogen enters the living world from the atmosphere through nitrogen-fixing bacteria. This nitrogen and nitrogenous waste from animals is then processed back into gaseous nitrogen by soil bacteria, which also supply terrestrial food webs with the organic nitrogen they need. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

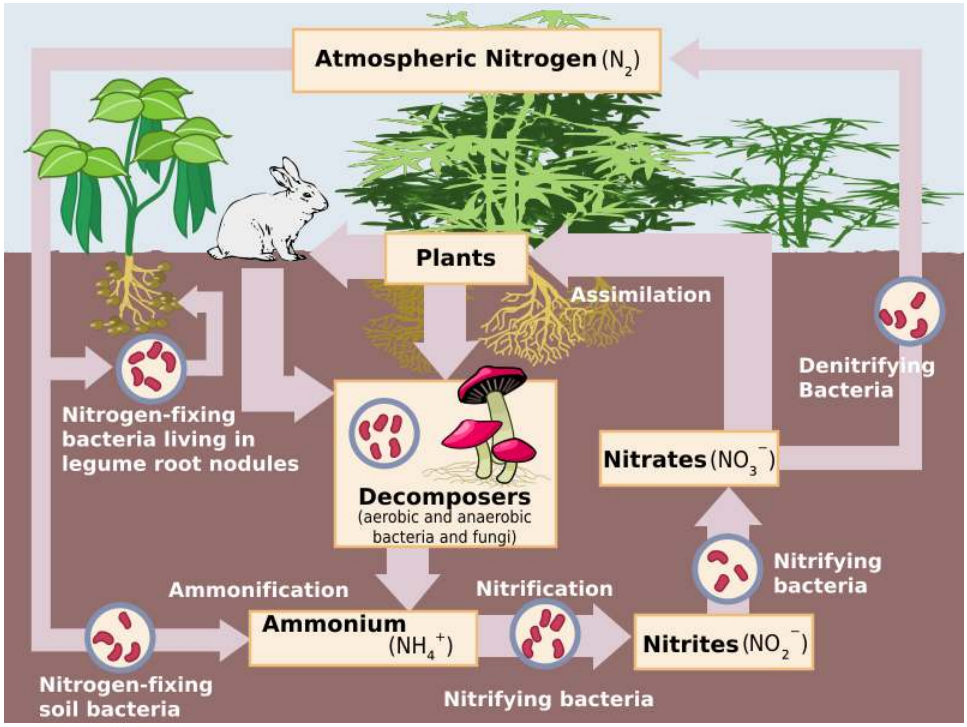


Figure 2.10.2: In the nitrogen cycle, nitrogen-fixing bacteria in the soil or legume root nodules convert nitrogen gas (N_2) from the atmosphere to ammonium (NH_4^+). Nitrification occurs when bacteria convert ammonium to nitrites (NO_2^-) and then to nitrates (NO_3^-). Nitrates re-enter the atmosphere as nitrogen gas through denitrification by bacteria. Plants assimilate ammonium and nitrates, producing organic nitrogen, which is available to consumers. Decomposers, including aerobic and anaerobic bacteria and fungi, break down organic nitrogen and release ammonium through ammonification. (credit: "Nitrogen cycle" by Johann Dréo & Raeky is licensed under CC BY-SA 3.0)

Three processes are responsible for most of the nitrogen fixation in the biosphere. The first is **atmospheric fixation** by lightning. The enormous energy of lightning breaks nitrogen molecules and enables their atoms to combine with oxygen in the air forming nitrogen oxides. These dissolve in rain, forming nitrates, that are carried to the earth. Atmospheric nitrogen fixation probably contributes some 5-8% of the total nitrogen fixed. The second process is **industrial fixation.** Under great pressure, at a temperature of 600°C (1112°F), and with the use of a **catalyst** (which facilitates chemical reactions), atmospheric nitrogen and hydrogen can be combined to form ammonia (NH_3). Ammonia can be used directly as fertilizer, but most of it is further processed to urea and ammonium nitrate (NH_4NO_3).

The third process is **biological fixation** by certain free-living or symbiotic bacteria, which incorporate nitrogen into their macromolecules. Cyanobacteria live in most aquatic ecosystems where sunlight is present; they play a key role in nitrogen fixation. Nitrogen-fixing cyanobacteria are essential to maintaining the fertility of semi-aquatic environments like rice paddies. Free-living bacteria, such as *Azotobacter*, are also important nitrogen fixers. Some nitrogen fixing bacteria form a symbiotic relationship with plants in the legume family, which includes beans, peas, soybeans, alfalfa, and clovers (figure 2.10.3). *Rhizobium* bacteria live symbiotically in the root nodules of legumes (such as peas, beans, and peanuts) and provide them with the organic nitrogen they need. Some nitrogen-fixing bacteria even establish symbiotic relationships with animals, e.g., termites and "shipworms" (wood-eating bivalves). Although the first stable product of the process is ammonia, this is quickly incorporated into protein and other organic nitrogen compounds.



Figure 2.10.3: Nitrogen-fixing bacteria live in the spherical nodules of this soybean root. Image by United Soybean Board (CC-BY).

Organic nitrogen is especially important to the study of ecosystem dynamics since many ecosystem processes, such as primary production and decomposition, are limited by the available supply of nitrogen. Plants and other producers directly use ammonium and nitrates to make organic molecules through the process of **assimilation (**Figure 2.10.2). This nitrogen is now available to consumers. Consumers excrete organic nitrogen compounds that return to the environment. Additionally dead organisms at each trophic level contain organic nitrogen.

As shown in Figure 2.10.2, the nitrogen that enters living systems by nitrogen fixation is eventually converted from organic nitrogen back into nitrogen gas by bacteria. This process occurs in three steps in terrestrial systems: ammonification, nitrification, and denitrification. First, the **ammonification** or **nitrogen mineralization** process converts nitrogenous waste from living organisims or the remains of dead organisms into ammonium (NH_4^+) by certain bacteria and fungi. Second, this ammonium is then converted to nitrites (NO_2^-) and then nitrates (NO_3^-) by nitrifying bacteria and archaea, such as Nitrosomonas or *Nitrobacter*, through the process of **nitrification**. In addition, both soil and the ocean contain **archaeal** microbes, assigned to the Crenarchaeota, that convert ammonia to nitrites. They are more abundant than the nitrifying bacteria and may turn out to play an important role in the nitrogen cycle.. Like ammonium, nitrites and nitrates are found in water and the soil. Some nitrates are converted back into nitrogen gas, which is released into the atmosphere. The process, called **denitrification**, is conducted by bacteria, such as *Pseudomonas* and *Clostridium*, which use nitratewhen decomposing organic matter in the absence of oxygen. In the process of denitrification several intermediates are formed and may be released to the atmosphere including nitric oxide (NO) and nitrous oxide (N_2O, a greenhouse gas). Under anaerobic conditions in marine and freshwater systems other species of bacteria are able to oxidize ammonia with nitrite forming nitogen gas in a process called **anammox** (anaerobic ammonia oxidation).

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.[1]

Human Alteration of the Nitrogen Cycle

Human activity can release nitrogen into the environment 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. Humans are also increasing the amount of reactive nitrogen in the environment by the cultivation of nitrogen fixing crops, such as soybeans. If the nitrogen fixation from leguminous crops (e.g. beans, alfalfa) is included, then the anthropogenic flux of nitrogen from the atmosphere to the land exceeds natural fluxes to the land. Atmospheric nitrogen (other than N_2) is associated with several effects on Earth's ecosystems including the production of

acid deposition (as nitric acid, HNO_3), also known as acid rain. Acid deposition damages healthy trees, destroys aquatic systems and erodes building materials such as marble and limestone. Like carbon dioxide, nitrous oxide (N_2O) is a greenhouse gas, potentially causing climate change when released during denitrification.

Humans are primarily dependent on the nitrogen cycle as a supporting ecosystem service for crop and forest productivity. Nitrogen fertilizers are added to enhance the growth of many crops and plantations (figure 2.10.4). The enhanced use of fertilizers in agriculture was a key feature of the green revolution that boosted global crop yields in the 1970s. The industrial production of nitrogen-rich fertilizers has increased substantially over time and now matches more than half of the input to the land from biological nitrogen fixation (90 megatons = 1 million tons of nitrogen each year). If the nitrogen fixation from legume crops is included, then the anthropogenic flux of nitrogen from the atmosphere to the land exceeds natural fluxes to the land. Fertilizers are washed into lakes, streams, and rivers by surface runoff, resulting in saltwater and freshwater **eutrophication**, a process whereby nutrient runoff causes the overgrowth of algae, the depletion of oxygen, and death of aquatic fauna. Excess nitrates in water supplies have also been linked to human health problems.



Figure 2.10.4**:** Fertilizer containing nitrogen is conventionally applied at large scales in agriculture. Image by Bob Nichols, USDA Natural Resources Conservation Service (public domain).

Efforts to reduce nitrogen pollution focus on increasing the efficiency of synthetic fertilizer use, altering feeding of animals to reduce nitrogen content in their excreta, and better processing of livestock waste and sewage sludge to reduce ammonia release. At the same time, increasing demand for food production from a growing global population with a greater appetite for meat is driving greater total fertilizer use, so there is no guarantee that better practices will lead to a reduction in the overall amount of nitrogen pollution.

Footnotes

1. 1 Scott L. Morford, Benjamin Z. Houlton, and Randy A. Dahlgren, “Increased Forest Ecosystem Carbon and Nitrogen Storage from Nitrogen Rich Bedrock,” *Nature* 477, no. 7362 (2011): 78–81.

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2.11: Phosphorus Cycle

Key Points

- Phosphorus, a major component of nucleic acid and phospholipids, also makes up the supportive components of our bones; it is often necessary for growth in aquatic ecosystems.
- Phosphates (PO_4^{3-}) are sent into rivers, lakes, and the ocean by leaching and natural surface runoff.
- Phosphate-containing ocean sediments slowly move to land by the uplifting of areas of the earth's surface.
- Excess phosphorus and nitrogen in the ecosystem leads to the death of many organisms, causing dead zones.
- Dead zones are caused by by eutrophication, oil spills, dumping of toxic chemicals, and other human activities.

The Phosphorus Cycle

Phosphorus is an essential nutrient for living processes; it is a major component of nucleic acid s, both DNA and RNA; of phospholipids, the major component of cell membranes; and, as calcium phosphate, makes up the supportive components of our bones. Phosphorus is often the limiting nutrient (necessary for growth) in aquatic, particularly freshwater, ecosystems. Several forms of nitrogen (nitrogen gas, ammnoium, nitrates, etc.) were involved in the nitrogen cycle, but phosphorus remains primarily in the form of the phosphate ion (PO_4^{3-}). Also in contrast to the nitrogen cycle, there is no form of phosphorus in the atmosphere. 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.

Rocks are a reservoir for phosphorus, and these rocks have their 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 2.11.1). Phosphorus is also reciprocally exchanged between phosphate dissolved in the ocean and marine ecosystems. 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.

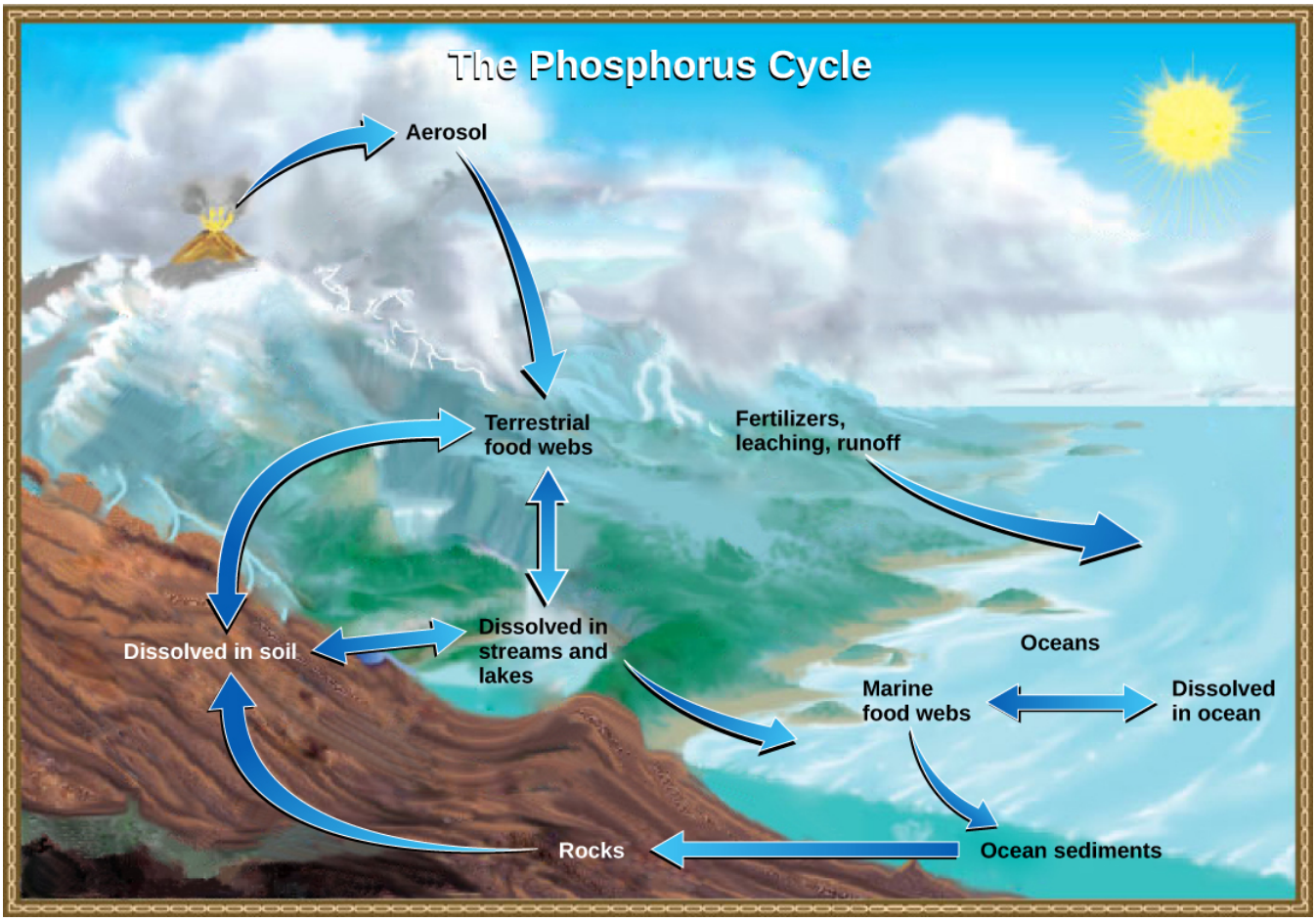


Figure 2.11.5: In nature, phosphorus exists as the phosphate ion (PO_4^{3-}). Weathering of rocks and volcanic activity releases phosphate into the soil, water, and air, where it becomes available to terrestrial food webs. Phosphate enters the oceans in surface runoff, groundwater flow, and river flow. Phosphate dissolved in ocean water cycles into marine food webs. Some phosphate from the marine food webs falls to the ocean floor, where it forms sediment. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

Marine birds play a unique role in the phosphorous cycle. These birds take up phosphorous from ocean fish. Their droppings on land (**guano**) contain high levels of phosphorous and are sometimes mined for commercial use. A 2020 study estimated that the **ecosystem services** (natural processes and products that benefit humans) provided by guano are worth $470 million per year.

Weathering of rocks releases phosphates into the soil and bodies of water. Plants can assimilate phosphates in the soil and incorporate it into organic molecules, making phosphorus available to consumers in terrestrial food webs. Waste and dead organisms are decomposed by fungi and bacteria, releasing phosphates back into the soil. Some phosphate is leached from the soil, entering into rivers, lakes, and the ocean. Primary producers in aquatic food webs, such as algae and photosynthetic bacteria, assimilate phosphate, and organic phosphate is thus available to consumers in aquatic food webs. Similar to terrestrial food webs, phosphorus is reciprocally exchanged between phosphate dissolved in the ocean and organic phosphorus in marine organisms.

The movement of phosphorus from rock to living organisms is normally a very slow process, but some human activities speed up the process. Phosphate-bearing rock is often mined for use in the manufacture of fertilizers and detergents. This commercial production greatly accelerates the phosphorous cycle. In addition, runoff from agricultural land and the release of sewage into water systems can cause a local overload of phosphate. The increased availability of phosphate can cause overgrowth of algae. This reduces the oxygen level, causing eutrophication and the destruction of other aquatic species.

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2.12: Eutrophication and Dead Zones

Eutrophication and Dead Zones

Nutrients in soil and water are generally beneficial when they exist at naturally occurring levels. Nitrogen fertilizers have been applied to farm fields for decades in order to maximize production of agricultural lands. However, an unintended consequence is that the same nutrients can be detrimental to aquatic ecosystems when introduced excessively for agricultural or other purposes. Nitrogen (N) and Phosphorus (P) are introduced by fertilizers that are used intensively in agriculture, as well as golf courses and some lawns and gardens. Farm animal waste and sewage also provide large amounts of reactive N and P. Phosphorus was formerly used heavily as an additive in laundry and dishwater detergents, but since the 1970's it has been phased out in both through a combination of state and federal regulations. Overall, our modern society has altered the global N and P cycles such that there is an overabundance in many settings.

Excessive nutrients (not utilized) are often washed into drainage ways, streams, and rivers during rainfall and storm events. **Eutrophication** occurs when excess phosphorus and nitrogen from fertilizer runoff or sewage causes excessive growth of algae. Algal blooms that block light and therefore kill aquatic plants in rivers, lakes, and seas. 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**, large areas in lakes and oceans near the mouths of rivers that are periodically depleted of their normal flora and fauna, and for massive fish kills, which often occur during the summer months (figure 2.12.1). There are more than 500 dead zones worldwide. Phosphate and nitrate runoff from fertilizers also negatively affect several lake and bay ecosystems including the Chesapeake Bay in the eastern United States.

One of the worst dead zones is off the coast of the United States in the Gulf of Mexico (figure 2.12.1). Fertilizer runoff from the Mississippi River basin created a dead zone, which reached its peak size of 8,776 square miles in 2017. The Mississippi River dumps high-nutrient runoff from its drainage basin that includes vast agricultural lands in the American Midwest. Increased algal growth produced by these nutrients has affected important shrimp fishing grounds in the Gulf. The primary source of the nutrients is the heavily tile-drained areas of farmland in the Midwest corn and soybean belt (SW Minnesota, N Iowa, NE Illinois, N Indiana and NW Ohio). Improved soil drainage systems over the past century or more have allowed for effective transport of nitrate compounds as stormwater runoff into drainage basins (Ohio River, Wabash River, Illinois River, Missouri River, etc.) that feed into the Mississippi River. In other words, the same drainage tiles that allow for the agricultural benefit of having rich bottomland/wetland soils in production, have the disadvantage of increased and more rapid movements of nitrate solutes to the Gulf of Mexico. Such large-scale problems, across state governmental boundaries, can only be fully addressed in the future with a national system of incentives, regulations, or laws.

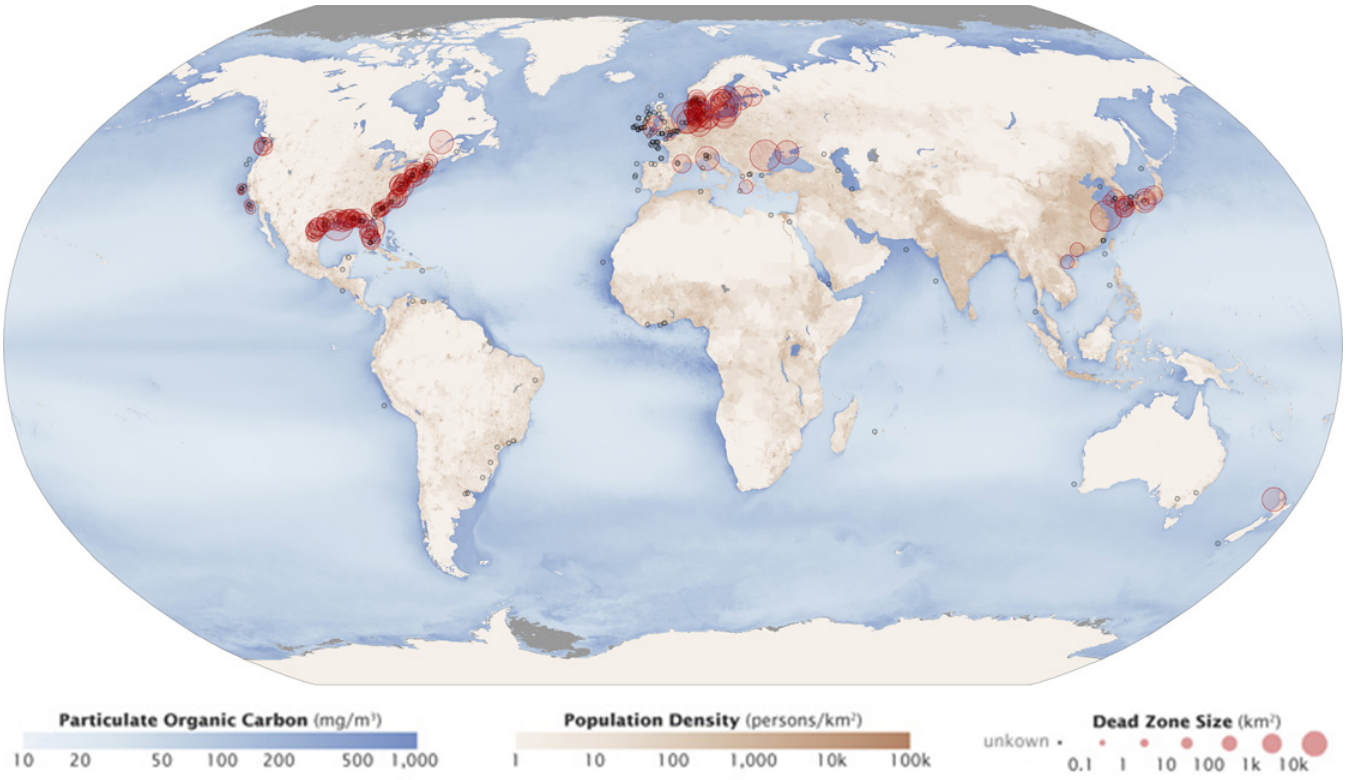


Figure 2.12.1: Dead zones occur when phosphorus and nitrogen from fertilizers cause excessive growth of microorganisms, which depletes oxygen and kills fauna. This map shows dead zones around the world in 2008. Worldwide, large dead zones are found in coastal areas of high population density. (credit: NASA Earth Observatory)

In addition to fertilizers, Nitrogen inputs to watersheds can also include atmospheric deposition, livestock waste, and sewage, but nitrogen fertilizers comprise a significant majority of the input to monitored streams, particularly in springtime when much fertilizer is applied. Possible solutions to this problem include encouraging farmers to apply a more limited quantity of fertilizer in the spring (only as much as necessary), rather than in the fall, to allow for considerably less time for stormwater or meltwater runoff. Other solutions include maintaining cover crops, or restoring wetlands in key locations to contain nitrate losses. An overall strategy that limits the excess capacity of nutrients can simultaneously benefit farmers (by limiting cost), the ecology of stream watersheds and coastal ecosystems (also locally stressed by oil spills and other pollution). Over the long term, more efforts will need to be made in the Mississippi River Basin, and globally in similarly stressed agricultural or urban watersheds (figure 2.12.1), to improve the health and sustainability of our soil, land, and aquatic ecosystems.

Everyday Connection: Chesapeake Bay

The Chesapeake Bay has long been valued as one of the most scenic areas on Earth; it is now in distress and is recognized as a declining ecosystem. In the 1970s, the Chesapeake Bay was one of the first ecosystems to have identified dead zones, which continue to kill many fish and bottom-dwelling species, such as clams, oysters, and worms (figure 2.12.2). Several species have declined in the Chesapeake Bay due to surface water runoff containing excess nutrients from artificial fertilizer used on land. The source of the fertilizers (with high nitrogen and phosphate content) is not limited to agricultural practices. There are many nearby urban areas and more than 150 rivers and streams empty into the bay that are carrying fertilizer runoff from lawns and gardens. Thus, the decline of the Chesapeake Bay is a complex issue and requires the cooperation of industry, agriculture, and everyday homeowners.



(a) (b)

Figure 2.12.2: This (a) satellite image shows the Chesapeake Bay, an ecosystem affected by phosphate and nitrate runoff. A (b) member of the Army Corps of Engineers holds a clump of oysters being used as a part of the oyster restoration effort in the bay. (credit a: modification of work by NASA/MODIS; credit b: modification of work by U.S. Army)

Of particular interest to conservationists is the oyster population; it is estimated that more than 200,000 acres of oyster reefs existed in the bay in the 1700s, but that number has now declined to only 36,000 acres. Oyster harvesting was once a major industry for Chesapeake Bay, but it declined 88 percent between 1982 and 2007. This decline was due not only to fertilizer runoff and dead zones but also to overexploitation. Oysters require a certain minimum population density because they must be in close proximity to reproduce. Human activity has altered the oyster population and locations, greatly disrupting the ecosystem.

The restoration of the oyster population in the Chesapeake Bay has been ongoing for several years with mixed success. Not only do many people find oysters good to eat, but they also clean up the bay. Oysters are filter feeders, and as they eat, they clean the water around them. In the 1700s, it was estimated that it took only a few days for the oyster population to filter the entire volume of the bay. Today, with changed water conditions, it is estimated that the present population would take nearly a year to do the same job.

Restoration efforts have been ongoing for several years by non-profit organizations, such as the Chesapeake Bay Foundation. The restoration goal is to find a way to increase population density so the oysters can reproduce more efficiently. Many disease-resistant varieties (developed at the Virginia Institute of Marine Science for the College of William and Mary) are now available and have been used in the construction of experimental oyster reefs. Efforts to clean and restore the bay by Virginia and Delaware have been hampered because much of the pollution entering the bay comes from other states, which stresses the need for inter-state cooperation to gain successful restoration.

The new, hearty oyster strains have also spawned a new and economically viable industry—oyster aquaculture—which not only supplies oysters for food and profit, but also has the added benefit of cleaning the bay.

Suggested Supplementary Reading

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CHAPTER OVERVIEW

3: Evolution and Ecology

3.1: Adaptation and Natural Selection
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3.1: Adaptation and Natural Selection

What biological process is responsible for biodiversity?

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

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



Figure 3.2.1. The diversity of life on Earth is the result of evolution, a continuous process that is still occurring. (credit "wolf": modification of work by Gary Kramer, USFWS; credit "coral": modification of work by William Harrigan, NOAA; credit "river": modification of work by Vojtěch Dostál; credit "protozoa": modification of work by Sharon Franklin, Stephen Ausmus, USDA ARS; credit "fish" modification of work by Christian Mehlführer; credit "mushroom", "bee": modification of work by Cory Zanker; credit "tree": modification of work by Joseph Kranak)

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 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 3.1.1). 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]

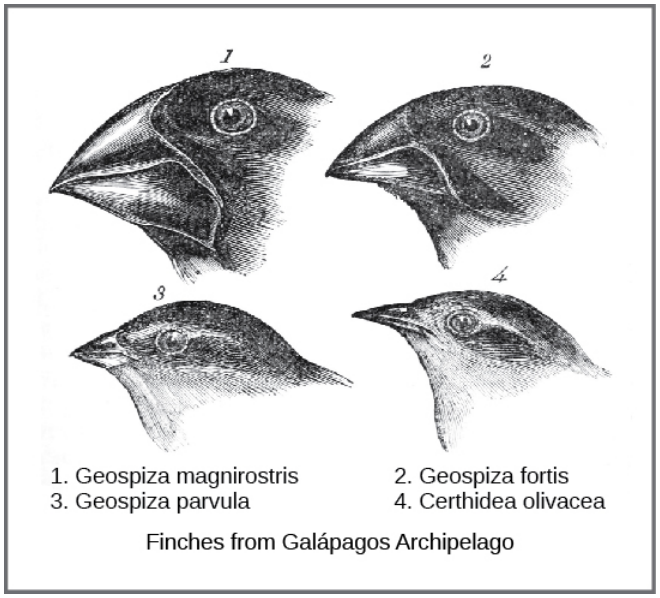


Figure 3.1.1: Darwin observed that beak shape varies among finch species. He postulated that the beak of an ancestral species had adapted over time to equip the finches to acquire different food sources. This illustration shows the beak shapes for four species of ground finch: 1. Geospiza magnirostris (the large ground finch), 2. G. fortis (the medium ground finch), 3. G. 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 3.1.2) 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 3.1.2: (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 3.1.3). 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.

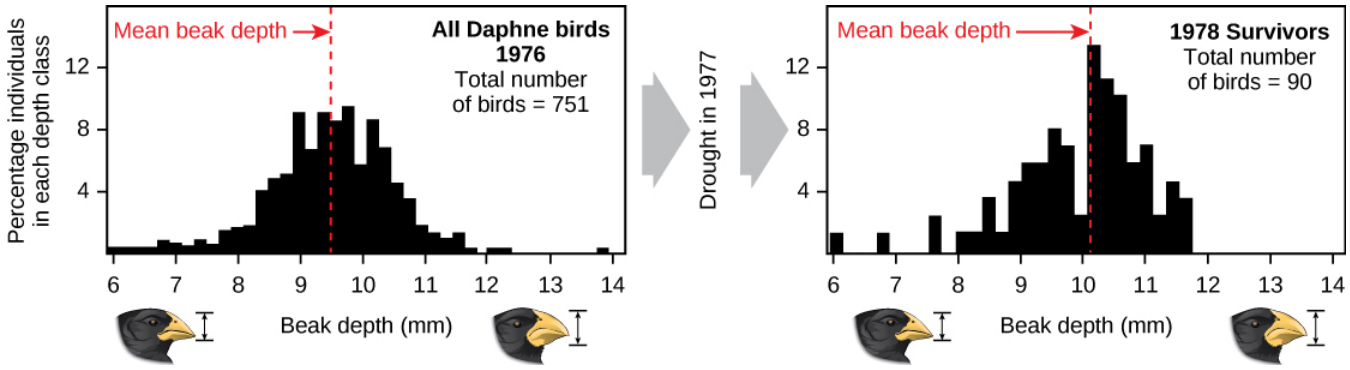


Figure 3.1.3: A drought on the Galápagos island of Daphne Major in 1977 reduced the number of small seeds available to finches, causing many of the small-beaked finches to die. This caused an increase in the finches' average beak size between 1976 and 1978.

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 3.1.4).



(a) (b)

Figure 3.1.4: Flowering plants evolved from a common ancestor. Notice that the (a) dense blazing star and (b) purple coneflower 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.

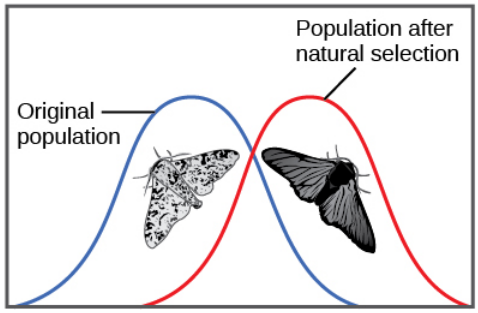
Population Genetics

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 3.1.5).



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.

Figure 3.1.5: 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.

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

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Glossary

adaptation

a heritable trait or behavior in an organism that aids in its survival in its present environment

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

convergent evolution

an evolution that results in similar forms on different species

divergent evolution

an evolution that results in different forms in two species with a common ancestor

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

homologous structure

a structure that is similar because of descent from a common ancestor

inheritance of acquired characteristics

a phrase 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

macroevolution

a broader scale of evolutionary changes seen over paleontological time

microevolution

the changes in a population's genetic structure (i.e., allele frequency)

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

modern synthesis

the overarching evolutionary paradigm that took shape by the 1940s and is generally accepted today

natural selection

the greater relative survival and reproduction of individuals in a population that have favorable heritable traits, leading to evolutionary change

population genetics

the study of how selective forces change the allele frequencies in a population over time

variation

the variety of alleles in a population

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3.2: What is Evolution?

At its simplest, **evolution** is any change in heritable traits in a population of organisms across generations. These changes may be the result of natural selection, genetic drift, mutation, etc – processes that we will consider in depth later in the course. All populations experience evolutionary change, as influenced by their environment, their interactions with other organisms, and random chance. Like ecology, we can consider evolution at different scales.

Microevolution is genetic change that occurs over small timescales and results in small changes in heritable traits. For example, Drs. Peter and Rosemary Grant studied medium ground finches (*Geospiza fortis*, Fig 1.3.1) in the Galápagos Islands for over 40 years, tracking the body size, beak size, weight, and other traits in the entire population over numerous generations. In 1977 a major drought hit the island of Daphne Major where the Grants were performing their study. The drought caused a change in the vegetation of the island, whose seeds are the food source for the ground finches. In the generation following the drought, the Grants documented an increase in the beak size of the ground finches in response to the change in seeds on which they feed. This relatively small change in a heritable trait across generations represents a microevolutionary response to the 1977 drought.



Figure 3.2.1: *A medium ground finch, Geospiza fortis. Image from Wikimedia Commons*[1].

Macroevolution is genetic change that occurs over long time scales, resulting in large changes in heritable traits in a population; changes large enough that we consider this population a unique taxonomic group, or species. Macroevolution is sometimes also termed **speciation** (the process by which a new species arises). This is the scale of evolutionary change that most people think of when someone mentions 'evolution'. For example, the medium ground finch is not the only finch species in the Galápagos Islands. The genus *Geospiza* contains nine species, all of which are found exclusively in the Galápagos Islands. Approximately 2 million years ago, the ancestor of these species migrated to the Galápagos Islands from South America. Between then and now, the birds migrated throughout the Galápagos Islands and across generations experienced different microevolutionary changes. Eventually, these small differences accumulated to the point that individuals of different populations are genetically distinct, no longer interbreed with one another, and perform different ecological roles in the habitat (for instance, some feed on seeds, while others feed on insects). Consequently, we now consider them different species. *Geospiza* is not the only group of finches on the Galápagos Islands - Figure 1.3.2 illustrates differences in head and beak shape between several finch groups on the Islands.



Figure 3.2.2: *Beak and head shape of two Geospiza finches and two other Galápagos finch species. Clockwise from top left: Geospiza magnirostris, Geospiza fortis, Certhidea olivacea, Camarhynchus parvulus. Image from Wikimedia Commons*[2].

It is important to note that microevolution and macroevolution are not different processes. Both relate to genetic changes in a population across generations; the only difference is the timescale on which the two operate. Macroevolution is the accumulation of microevolutionary changes over a long period of time to the point that the population is unique from other populations, and is considered a distinct species.

Image Credits

1. https://commons.wikimedia.org/wiki/File:Geospiza_fortis.jpg
2. https://commons.wikimedia.org/wiki/File:Darwin%27s_finches.png

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3.3: 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 3.3.1). 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.

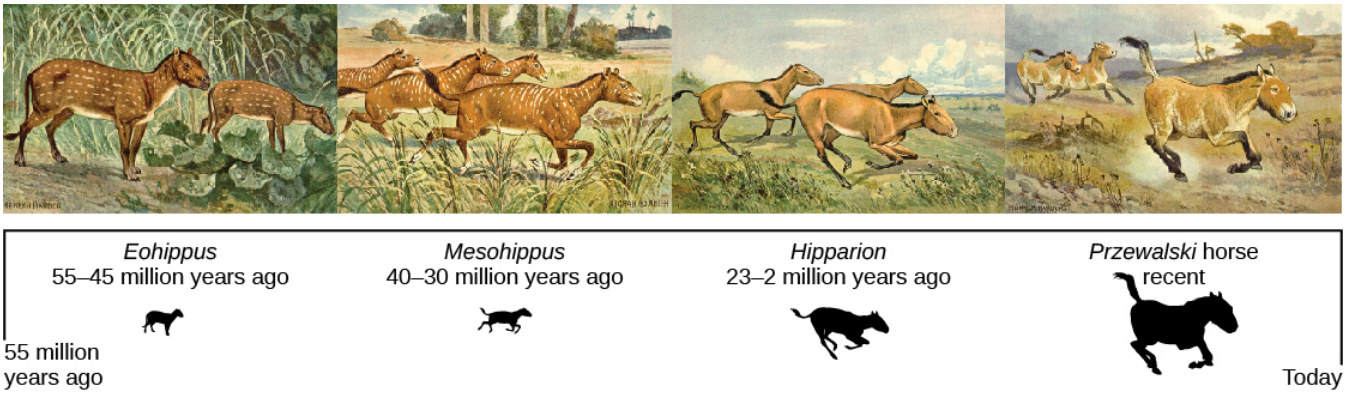


Figure 3.3.1**:** This illustration shows an artist's renderings of these species derived from fossils of the evolutionary history of the horse and its ancestors. The species depicted are only four from a very diverse lineage that contains many branches, dead ends, and adaptive radiations. One of the 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 3.3.2). 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.

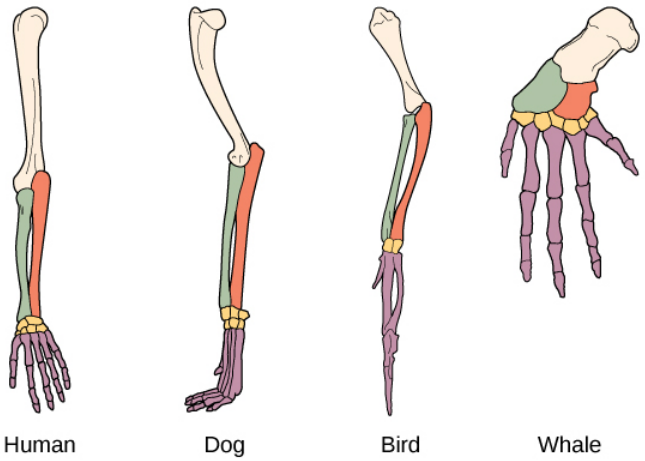


Figure 3.3.2**:** The similar construction of these appendages indicates that these organisms share a common ancestor.

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 3.3.3). 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 3.3.3**:** 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 3.3.4).

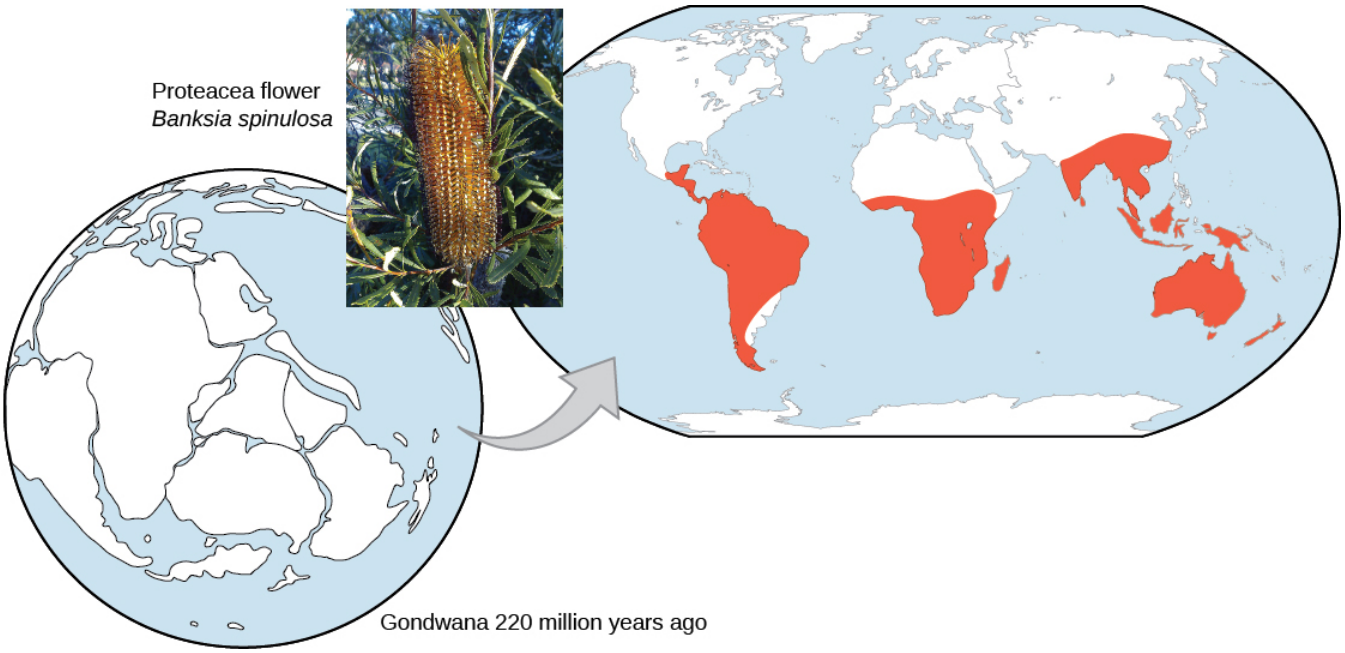


Figure 3.3.4**:** The Proteacea family of plants evolved before the supercontinent Gondwana broke up. Today, members of this plant family are found throughout the southern hemisphere (shown in red). (credit "Proteacea flower": modification of work by "dorofofoto"/Flickr)

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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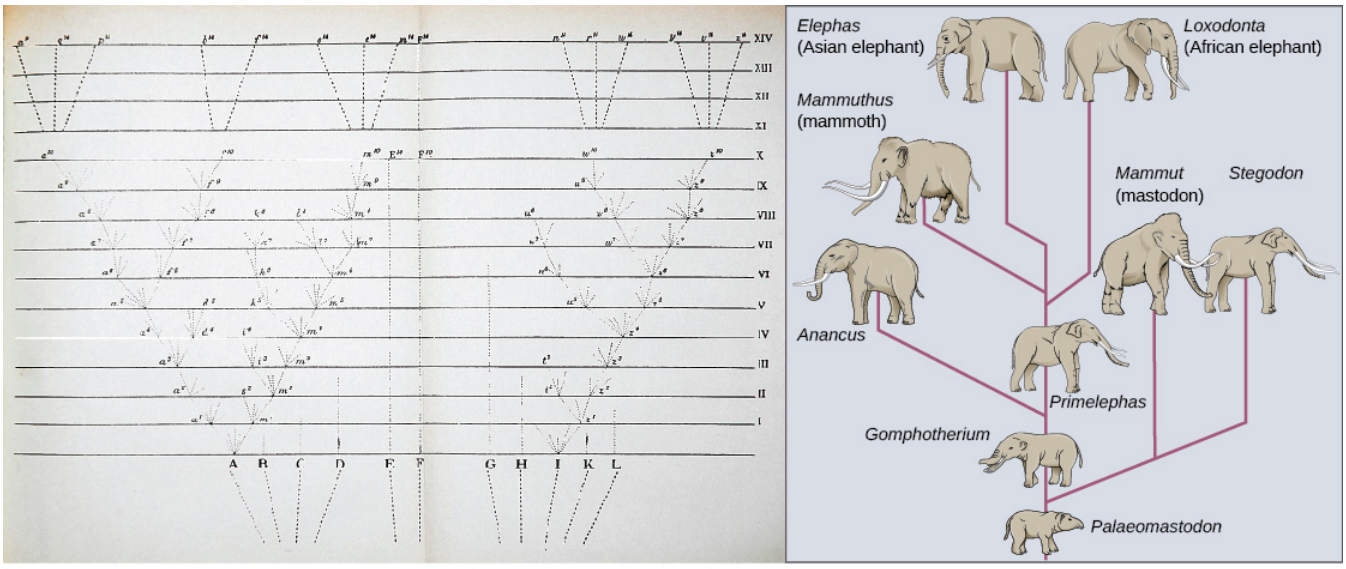
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3.4: Speciation

The biological definition of species, which works for sexually reproducing organisms, is a group of actually or potentially interbreeding individuals. According to this definition, one species is distinguished from another by the possibility of matings between individuals from each species to produce fertile offspring. There are exceptions to this rule. Many species are similar enough that hybrid offspring are possible and may often occur in nature, but for the majority of species this rule generally holds. In fact, the presence of hybrids between similar species suggests that they may have descended from a single interbreeding species and that the speciation process may not yet be completed.

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 3.4.1**a**). 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 3.4.1**:** 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 3.4.2). 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]

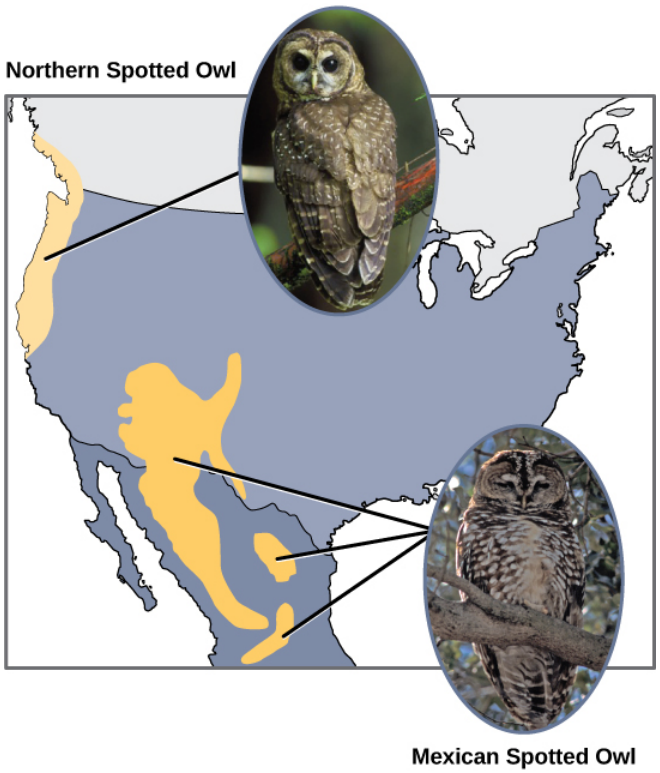


Figure 3.4.2**:** The northern spotted owl and the Mexican spotted owl inhabit geographically separate locations with different climates and ecosystems. The owl is an example of incipient speciation. (credit "northern spotted owl": modification of work by John and Karen Hollingsworth, USFWS; credit "Mexican 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 3.4.3). 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 3.4.3.

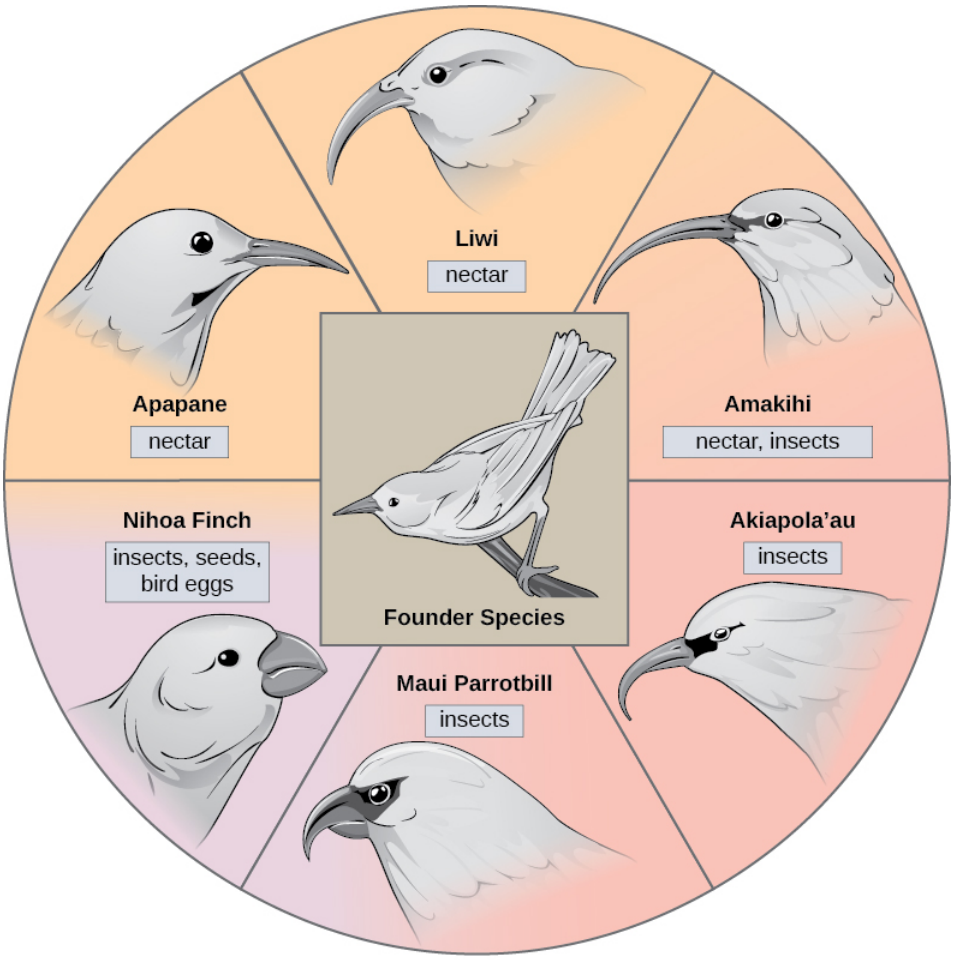


Figure 3.4.3**:** The honeycreeper birds illustrate adaptive radiation. From one original species of bird, multiple others evolved, each with its own distinctive characteristics.

Notice the differences in the species' beaks in Figure 3.4.3. 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 3.4.4). 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.

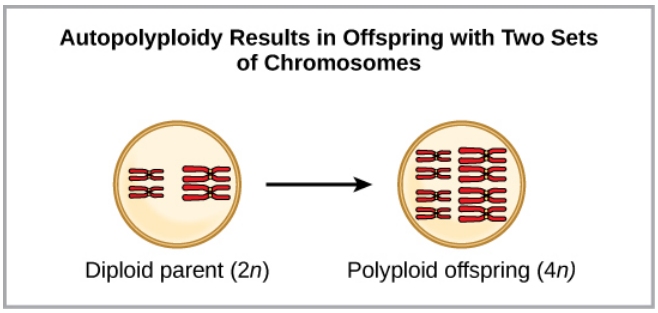


Figure 3.4.4**:** Autopolyploidy results when mitosis is not followed by cytokinesis.

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 3.4.5 illustrates one possible way an allopolyploidy can form. Notice how it takes two generations, or two reproductive acts, before the viable fertile hybrid results.

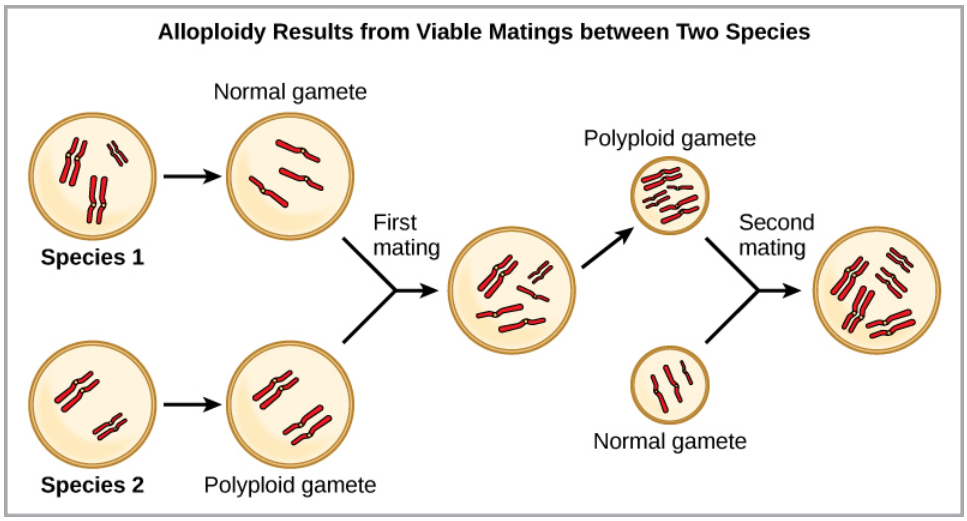


Figure 3.4.5**:** Alloploidy results when two species mate to produce viable offspring. In the example shown, a normal gamete from one species fuses with a polyploid gamete from another. Two matings are necessary to produce viable offspring.

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 3.4.6 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.

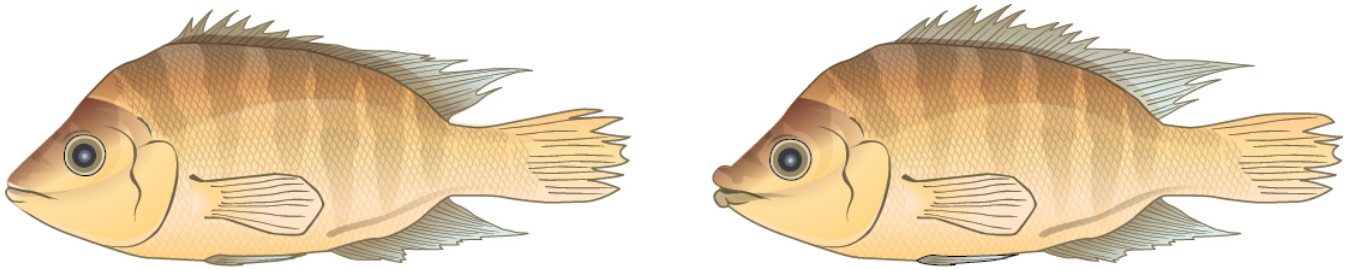


Figure 3.4.6**:** Cichlid fish from Lake Apoyeque, Nicaragua, show evidence of sympatric speciation. Lake Apoyeque, a crater lake, is 1800 years old, but genetic evidence indicates that the lake was populated only 100 years ago by a single population of cichlid fish. Nevertheless, two populations with 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 measureable 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.

Glossary

adaptive radiation

a speciation when one species radiates out to form several other species

allopatric speciation

a speciation that occurs via a geographic separation

dispersal

an allopatric speciation that occurs when a few members of a species move to a new geographical area

speciation

a formation of a new species

sympatric speciation

a speciation that occurs in the same geographic space

vicariance

an allopatric speciation that occurs when something in the environment separates organisms of the same species into separate groups

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3.5: 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

Contributors and Attributions

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3.6: Organizing Life on Earth

All life on Earth evolved from a common ancestor. Biologists map how organisms are related by constructing phylogenetic trees. In other words, 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 3.6.1. Notice that from a single point, the three domains of Archaea, Bacteria, and Eukarya diverge and then branch repeatedly. The small branch that plants and animals (including humans) occupy in this diagram shows how recently these groups had their origin compared with other groups.

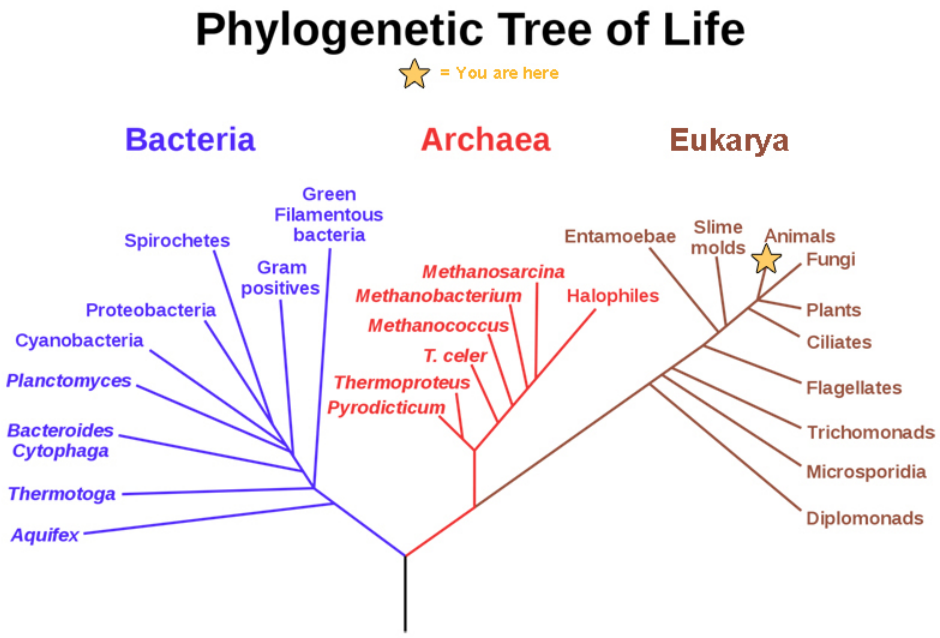


Figure 3.6.1**:** In the evolution of life on Earth, the three domains of life—Archaea, Bacteria, and Eukarya—branch from a single point. (credit: modification of work by Eric Gaba)

The phylogenetic tree in Figure 3.6.1 illustrates the pathway of evolutionary history. The pathway can be traced from the origin of life to any individual species by navigating through the evolutionary branches between the two points. Also, by starting with a single species and tracing backward to any branch point, the organisms related to it by various degrees of closeness can be identified.

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.

Many disciplines within the study of 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.

Scientists continue to discover new species of life on Earth as well as new character information, thus trees change as new data arrive.

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 3.6.2. 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 3.6.2 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

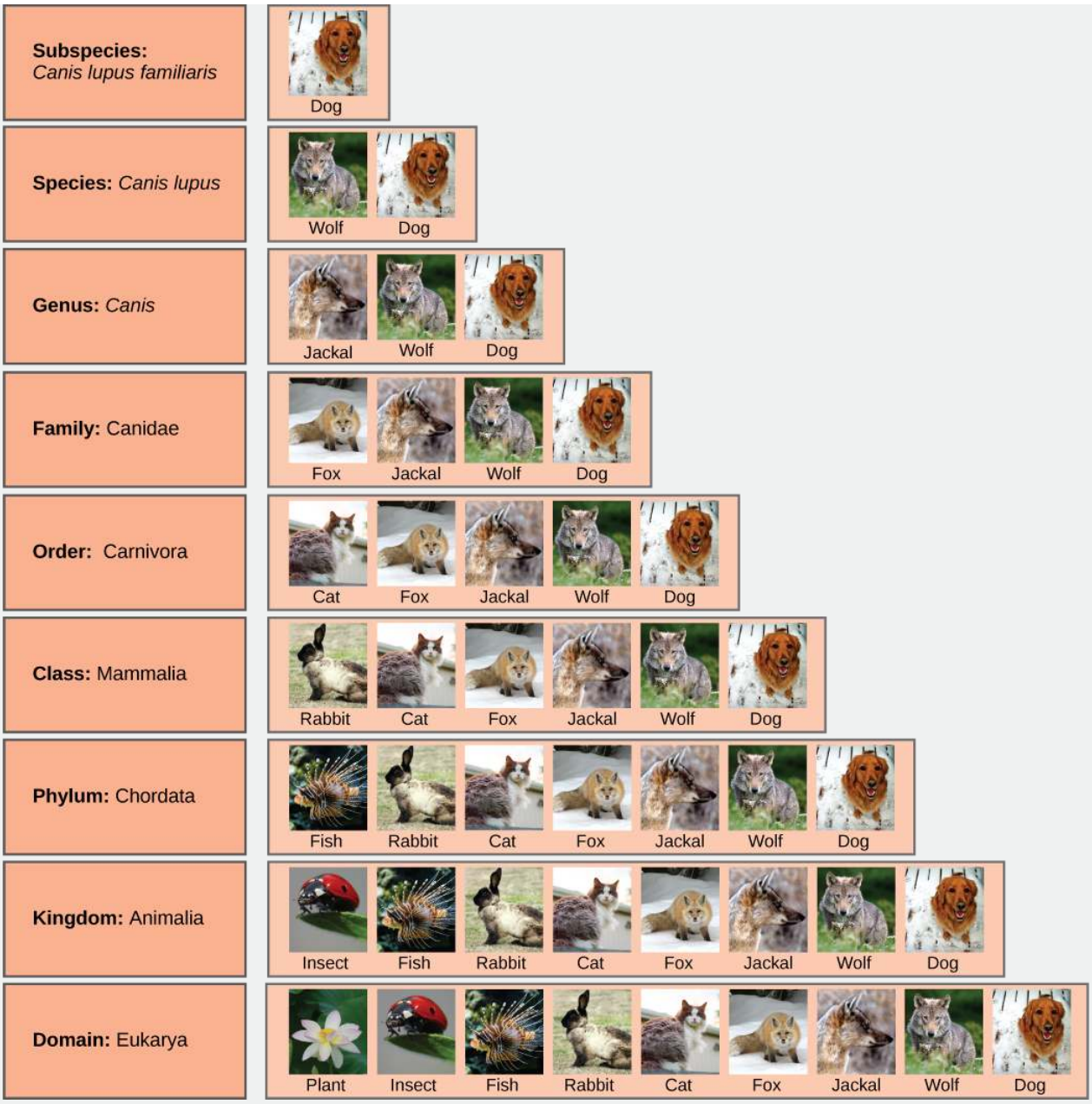


Figure 3.6.2**:** At each sublevel in the taxonomic classification system, organisms become more similar. Dogs and wolves are the same species because they can breed and produce viable offspring, but they are different enough to be classified as different subspecies. (credit “plant”: modification of 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 3.6.3. Shared characteristics are used to construct phylogenetic trees. The point where a split occurs in a tree, called a 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 branch point, or split, 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.

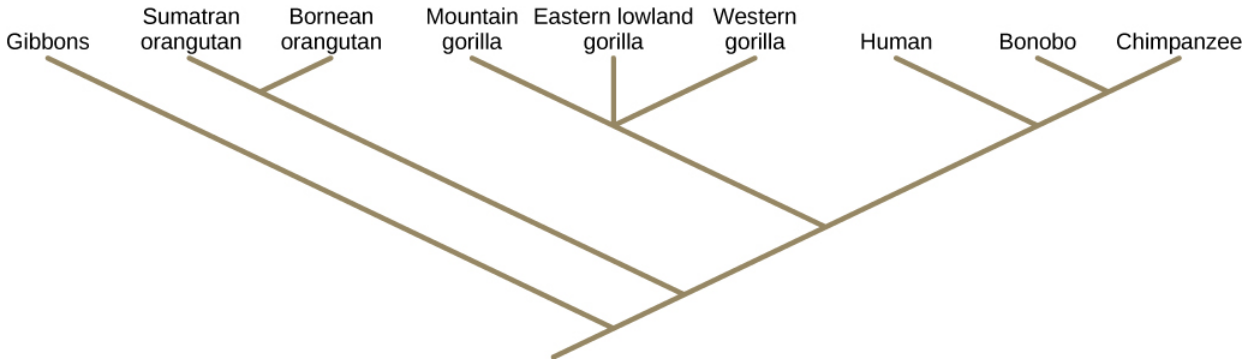


Figure 3.6.3: A phylogenetic tree is rooted and shows how different organisms, in this case the species and subspecies of living apes, evolved from a common ancestor.

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 3.6.4, 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.

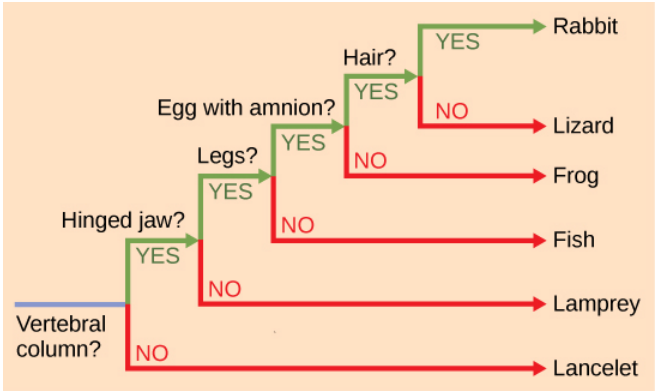


Figure 3.6.4: This phylogenetic tree is rooted by an organism that lacked a vertebral column. At each branch point, organisms with different characters are placed in different groups.

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 3.6.4 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 3.6.4, 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 3.6.4, 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 3.6.4, 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 3.6.2: 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.

Glossary

binomial nomenclature
a system of two-part scientific names for an organism, which includes genus and species names

branch point
a point on a phylogenetic tree where a single lineage splits to distinct new ones

class
the category in the taxonomic classification system that falls within phylum and includes orders

domain
the highest level category in the classification system and that includes all taxonomic classifications below it; it is the most inclusive taxon

family
the category in the taxonomic classification system that falls within order and includes genera

genus
the category in the taxonomic classification system that falls within family and includes species; the first part of the scientific name

kingdom
the category in the taxonomic classification system that falls within domain and includes phyla

order
the category in the taxonomic classification system that falls within class and includes families

phylogenetic tree
diagram used to reflect the evolutionary relationships between organisms or groups of organisms

phylogeny
evolutionary history and relationship of an organism or group of organisms

phylum
the category in the taxonomic classification system that falls within kingdom and includes classes

rooted
describing a phylogenetic tree with a single ancestral lineage to which all organisms represented in the diagram relate

sister taxa
two lineages that diverged from the same branch point

species
the most specific category of classification

systematics
the science of determining the evolutionary relationships of organisms

taxon
a single level in the taxonomic classification system

taxonomy
the science of classifying organisms

Contributors

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3.7: Introduction to Ecology

Learning Objectives

- Describe the study of ecology

An Introduction to Ecology

Ecology is the study of the interactions of living organisms with their environment. Within the discipline of ecology, researchers work at four specific levels, sometimes discretely and sometimes with overlap. These levels are organism, population, community, and ecosystem. In ecology, ecosystems are composed of dynamically interacting parts, which include organisms, the communities they comprise, and the non-living (abiotic) components of their environment. Ecosystem processes, such as primary production, pedogenesis (the formation of soil), nutrient cycling, and various niche construction activities, regulate the flux of energy and matter through an environment. These processes are sustained by organisms with specific life-history traits. The variety of organisms, called biodiversity, which refers to the differing species, genes, and ecosystems, enhances certain ecosystem services.

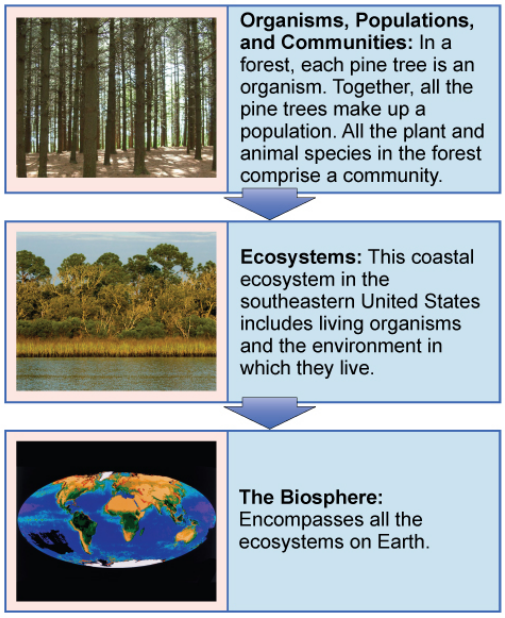


Figure 3.7.1: Levels of ecological study: Ecologists study several biological levels of organization, which include the organism, population, community, and ecosystem.

In essence, ecologists seek to explain:

- life processes
- interactions, interrelationships, behaviors, and adaptations of organisms
- the movement of materials and energy through living communities
- the successional development of ecosystems
- the abundance and distribution of organisms and biodiversity in the context of the environment

There are many practical applications of ecology in conservation biology, wetland management, natural resource management (agroecology, agriculture, forestry, agroforestry, fisheries), city planning (urban ecology), community health, economics, basic and applied science, and human social interaction (human ecology). Organisms and resources comprise ecosystems that, in turn, maintain biophysical feedback mechanisms that moderate processes acting on living (biotic) and nonliving (abiotic) components of the planet. Ecosystems sustain life-supporting functions and produce natural capital, such as biomass production (food, fuel, fiber, and medicine), the regulation of climate, global biogeochemical cycles, water filtration, soil formation, erosion control, flood protection, and many other natural features of scientific, historical, economic, or intrinsic value.

There are also many subcategories of ecology, such as ecosystem ecology, animal ecology, and plant ecology, which look at the differences and similarities of various plants in various climates and habitats. In addition, physiological ecology, or ecophysiology, studies the responses of the individual organism to the environment, while population ecology looks at the similarities and dissimilarities of populations and how they replace each other over time.

Finally, it is important to note that ecology is not synonymous with environment, environmentalism, natural history, or environmental science. It is also different from, though closely related to, the studies of evolutionary biology, genetics, and ethology.

Organismal Ecology



Figure 3.7.2: Karner blue butterfly: 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.

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 (pertaining to the study of form or structure), physiological, and behavioral. For instance, the Karner blue butterfly (*Lycaeides melissa samuelis*) is considered a specialist because the females preferentially oviposit (that is, lay eggs) on wild lupine. This preferential adaptation means that the Karner blue butterfly is highly dependent on the presence of wild lupine plants for its continued survival.



Figure 3.7.3: Wild lupine: The wild lupine (Lupinus perennis) is the host plant for the Karner blue butterfly.

After hatching, the larval caterpillars emerge to spend four to six weeks feeding solely on wild lupine. The caterpillars pupate (undergo metamorphosis), emerging as butterflies after about four weeks. The adult butterflies feed on the nectar of flowers of wild lupine and other plant species. A researcher interested in studying Karner blue butterflies at the organismal level might, in addition to asking questions about egg laying, ask questions about the butterflies' preferred temperature (a physiological question) or the behavior of the caterpillars when they are at different larval stages (a behavioral question).

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, a population, are called conspecifics. A population is identified, in part, by where it lives; its area of population may have natural or artificial boundaries. Natural boundaries might be rivers, mountains, or deserts, while examples of artificial boundaries include mowed grass or human-made structures such as roads. The study of population ecology focuses on the number of individuals in an area and how and why population size changes over time. Population ecologists are particularly interested in counting the Karner blue butterfly, for example, because it is classified as federally endangered. However, the distribution and density of this species are highly influenced by the distribution and abundance of wild lupine. 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 among 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, the larvae of the Karner blue butterfly form mutualistic relationships with ants. 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 the probability of survival when Karner blue butterfly larvae (caterpillars) are tended by ants. 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, the Karner blue butterfly larvae secrete 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.



Figure 3.7.4: Karner blue butterfly caterpillar: Karner blue butterfly caterpillars form beneficial interactions with ants. This mutualistic relationship is an example of a community ecological study, which aims to examine the interactions between different species living in an area.

Ecosystem Ecology

Ecosystem ecology is an extension of organismal, population, and community ecology. The ecosystem is composed of all the biotic components (living things) in an area along with that area's abiotic components (non-living things). Some of the abiotic components include air, water, and soil. Ecosystem biologists ask questions about how nutrients and energy are stored, along with how they move among organisms and the surrounding atmosphere, soil, and water.

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, through the biotic and abiotic portions of the ecosystem.

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Key Points

- Organismal ecology focuses on the morphological, physiological, and behavioral adaptations that let an organism survive in a specific habitat.
- Population ecology studies the number of individuals in an area, as well as how and why their population size changes over time.
- The Karner blue butterfly, an endangered species, makes a good model for both organismal and population ecology since it is dependent, as a population, on a specific plant that grows within specific areas, which, thus, influences butterfly distribution and numbers.
- Community ecology focuses on the processes driving interactions between differing species and their overall consequences.
- Ecosystem ecology studies all organismal, population, and community components of an area, as well as the non-living counterparts.
- The mutualistic relationship between the Karner blue butterfly and ants are of interest to community ecology studies since both species interact within an area and affect each other's survival rate; in turn, they are both affected by nutrient -poor soils, which

are part of the ecosystem ecology.

Key Terms

- **ecology**: the branch of biology dealing with the relationships of organisms with their environment and with each other
- **ecosystem**: a system formed by an ecological community and its environment that functions as a unit
- **ecophysiology**: the study of the relationships between, and adaptation of, the physiology of an organism and its environment
- **community**: a group of interdependent organisms inhabiting the same region and interacting with each other
- **conspecific**: an organism belonging to the same species as another
- **heterospecific**: an organism belonging to a different species to another

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3.8: Community Ecology

Populations typically do not live in isolation from other species. Populations that interact within a given habitat form a **community**. The number of species occupying the same habitat and their relative abundance is known as the **diversity** of the community. Areas with low species diversity, such as the glaciers of Antarctica, still contain a wide variety of living organisms, whereas the diversity of tropical rainforests is so great that it 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 *predation* describes individuals of one population that kill and then consume the individuals of another population. Population sizes of predators and prey in a community are not constant over time, and they may vary in cycles that appear to be related. The most often cited example of predator-prey population dynamics is seen in the cycling of the lynx (predator) and the snowshoe hare (prey), using 100 years of trapping data from North America (Figure 3.8.1). 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.

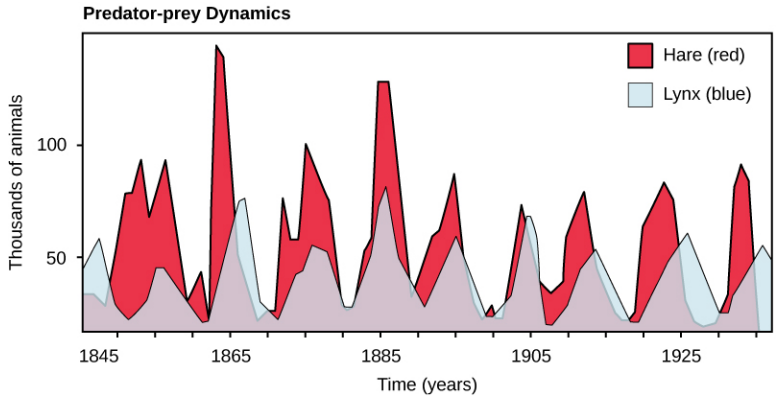


Figure 3.8.1. The cycling of snowshoe hare and lynx populations in Northern Ontario is an example of predator-prey dynamics.

Defense Mechanisms against Predation and Herbivory

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



(a) (b)

Figure 3.8.2. 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)

Mechanical defenses, such as the presence of armor in animals or thorns in plants, discourage predation and herbivory by discouraging physical contact (Figure 3.8.2a). Many animals produce or obtain chemical defenses from plants and store them to prevent predation. Many plant species produce secondary plant compounds that serve no function for the plant except that they are toxic to animals and discourage consumption. For example, the foxglove produces several compounds, including digitalis, that are extremely toxic when eaten (Figure 3.8.2b). (Biomedical scientists have repurposed the chemical produced by foxglove as a heart medication, which has saved lives for many decades.)

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 3.8.3a). In another example, the chameleon can change its color to match its surroundings (Figure 3.8.3b).



(a) (b)

Figure 3.8.3. (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 (Figure 3.8.4). They have bright red or orange coloration on their bellies, which they display to a potential predator to advertise their poisonous nature and discourage an attack. Warning coloration only works if a predator uses eyesight to locate prey and can learn—a naïve predator must experience the negative consequences of eating one before it will avoid other similarly colored individuals.



Figure 3.8.4. 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 3.8.5).



(a) (b)

Figure 3.8.5. 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 3.8.6 shows a variety of foul-tasting butterflies with similar coloration.



Figure 3.8.6. Several unpleasant-tasting *Heliconiusbutterfly 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**: 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 exact same niche in a habitat. In other words, different species cannot coexist in a community if they are competing for all the same resources. It is important to note that competition is bad for both competitors because it wastes energy. The competitive exclusion principle works because if there is competition between two species for the same resources, then natural selection will favor traits that lessen reliance on the shared resource, thus reducing competition. 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 3.8.7 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.

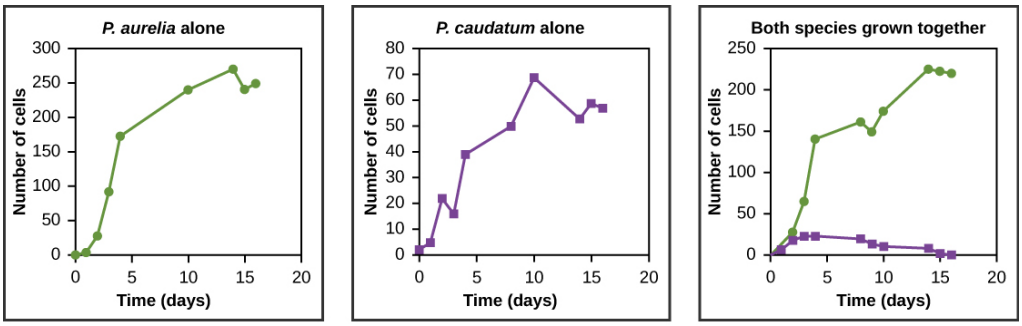


Figure 3.8.7. *Paramecium aurelia and Paramecium caudatum grow well individually, but when they compete for the same resources, the P. aurelia outcompetes the P. caudatum.*

Symbiosis

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



Figure 3.8.8. The southern masked-weaver is starting to make a nest in a tree in Zambezi Valley, Zambia. This is an example of a commensal relationship, in which one species (the bird) benefits, while the other (the tree) neither benefits nor is harmed. (credit: "Hanay"/Wikimedia Commons)

Commensalism occurs when one species benefits from a close prolonged interaction, while the other neither benefits or is harmed. Birds nesting in trees provide an example of a commensal relationship (Figure 3.8.8). The tree is not harmed by the presence of the nest among its branches. The nests are light and produce little strain on the structural integrity of the branch, and most of the leaves, which the tree uses to get energy by photosynthesis, are above the nest so they are unaffected. The bird, on the other hand, benefits greatly. If the bird had to nest in the open, its eggs and young would be vulnerable to predators. Many potential commensal

relationships are difficult to identify because it is difficult to prove that one partner does not derive some benefit from the presence of the other.

A second 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 3.8.9a). 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 3.8.9b). 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 3.8.9. (a) Termites form a mutualistic relationship with symbiotic protozoa in their guts, which allow both organisms to obtain energy from the cellulose the termite consumes. (b) Lichen is a fungus that has symbiotic photosynthetic algae living in close association. (credit a: modification of work by Scott Bauer, USDA; credit b: modification of work by Cory Zanker)

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

The reproductive cycles of parasites are often very complex, sometimes requiring more than one host species. A tapeworm causes disease in humans when contaminated and under-cooked meat such as pork, fish, or beef is consumed (Figure 3.8.10). 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.

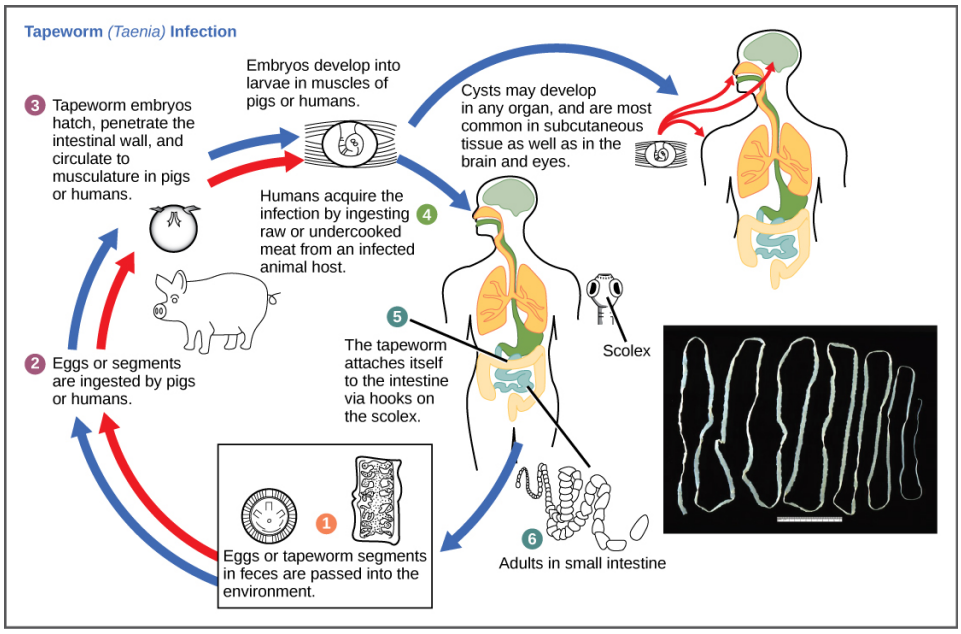


Figure 3.8.10. This diagram shows the life cycle of the tapeworm, a human worm parasite. (credit: modification of work by CDC)

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.

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 3.8.11). Species richness is related to latitude: the greatest species richness occurs near the equator and the lowest richness occurs near the poles. The exact reasons for this are not clearly understood. Other factors besides latitude influence species richness as well. For example, ecologists studying islands found that biodiversity varies with island size and distance from the mainland.

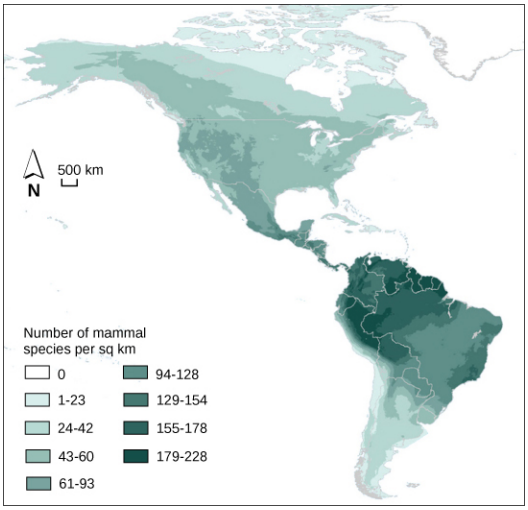


Figure 3.8.11. The greatest species richness for mammals in North America is associated in the equatorial latitudes. (credit: modification of work by NASA, CIESIN, Columbia University)

Relative 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.

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

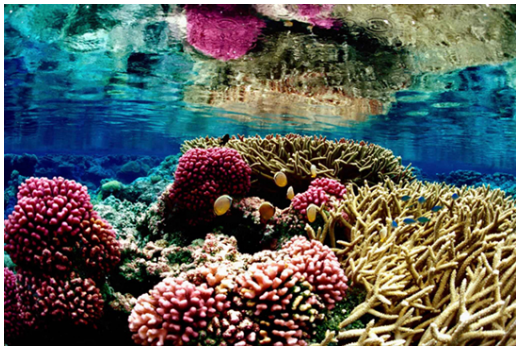


Figure 3.8.12. Coral is the foundation species of coral reef ecosystems. (credit: Jim E. Maragos, USFWS)

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 3.8.13). 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 3.8.13. Sea stars are keystone species of the intertidal zone.

BIOLOGY IN ACTION

Invasive species are non-native organisms that, when introduced to an area out of its native range, alter the community they invade. In the United States, invasive species like the purple loosestrife (*Lythrum salicaria*) and the zebra mussel (*Dreissena polymorpha*) have drastically altered the ecosystems they invaded. Some well-known invasive animals include the emerald ash borer (*Agrilus planipennis*) and the European starling (*Sturnus vulgaris*). Whether enjoying a forest hike, taking a summer boat trip, or simply walking down an urban street, you have likely encountered an invasive species.

One of the many recent proliferations of an invasive species concerns the Asian carp in the United States. Asian carp were introduced to the United States in the 1970s by fisheries (commercial catfish ponds) and by sewage treatment facilities that used the fish’s excellent filter feeding abilities to clean their ponds of excess plankton. Some of the fish escaped, and by the 1980s they had colonized many waterways of the Mississippi River basin, including the Illinois and Missouri Rivers.

Voracious feeders and rapid reproducers, Asian carp may outcompete native species for food and could lead to their extinction. One species, the grass carp, feeds on phytoplankton and aquatic plants. It competes with native species for these resources and alters nursery habitats for other fish by removing aquatic plants. In some parts of the Illinois River, Asian carp constitute 95 percent of the community's biomass. Although edible, the fish is bony and not desired in the United States.

The Great Lakes and their prized salmon and lake trout fisheries are being threatened by Asian carp. The carp are not yet present in the Great Lakes, and attempts are being made to prevent its access to the lakes through the Chicago Ship and Sanitary Canal, which is the only connection between the Mississippi River and Great Lakes basins. To prevent the Asian carp from leaving the canal, a series of electric barriers have been used to discourage their migration; however, the threat is significant enough that several states and Canada have sued to have the Chicago channel permanently cut off from Lake Michigan. Local and national politicians have weighed in on how to solve the problem. In general, governments have been ineffective in preventing or slowing the introduction of invasive species.

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



Figure 3.8.14. During primary succession in lava on Maui, Hawaii, succulent plants are the pioneer species. (credit: Forest and Kim Starr)

In both cases, the ecosystem starts with bare rock that is devoid of life. New soil is slowly formed as weathering and other natural forces break down the rock and lead to the establishment of hearty organisms, such as lichens and some plants, which are collectively known as **pioneer species** (Figure 3.8.14) because they are the first to appear. These species help to further break down the mineral-rich rock into soil where other, less hardy but more competitive species, such as grasses, shrubs, and trees, will grow and eventually replace the pioneer species. Over time the area will reach an equilibrium state, with a set of organisms quite different from the pioneer species.

Secondary succession

A classic example of secondary succession occurs in forests cleared by wildfire, or by clearcut logging (Figure 3.8.15). 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 trees. These organisms are called intermediate species. Eventually, over 150 years or more, the forest will reach its equilibrium point and resemble the community before the fire. This equilibrium state is referred to as the **climax community**, which will remain until the next disturbance. The climax community is typically characteristic of a given climate and geology. Although the community in equilibrium looks the same once it is attained, the equilibrium is a dynamic one with constant changes in abundance and sometimes species identities.

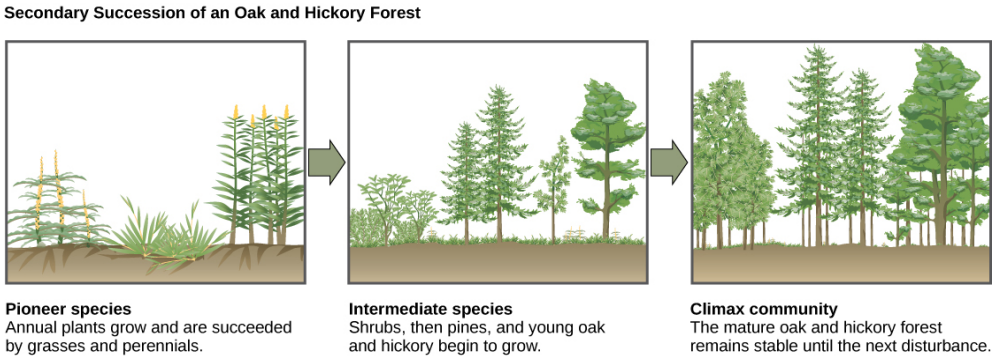


Figure 3.8.15. Secondary succession is seen in an oak and hickory forest after a forest fire. A sequence of the community present at three successive times at the same location is depicted.

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3.9: Symbiosis

Most of the interactions between species involve food, i.e., competing for the same food supply, eating (predation), and avoiding being eaten (avoiding predation). These interactions are often brief. There are many cases, however, where two species live in close association for long periods. Such associations are called **symbiotic** ("living together"). In symbiosis, at least one member of the pair benefits from the relationship. The other member may also benefit (**mutualism**), be relatively unaffected (**commensalism**), or may be injured (**parasitism**).

Types of Symbiosis

- Mutualism (both members benefit)
- Commensalism (one benefits, the other is unaffected)
- Parasitism (one benefits, the other is harmed)

Mutualism

Symbiotic relationships in which **each species benefits** are mutualistic. There are hundreds of examples of mutualism between a heterotroph and an alga.

- *Paramecium bursaria* is a ciliate that engulfs unicellular green algae into vacuoles within its cell.
  - The paramecium certainly benefits from the food synthesized by the alga. It can be cultured apart from the alga but then must be given extra food.
  - The alga presumably benefits from the carbon dioxide produced by its host as well as the host's ability to transport it to a spot where there is ample light.
- Many other aquatic animals, such as sponges, sea anemones, worms, and clams, also harbor algae within their cells which lets them get food from the photosynthesis of their partner.

Mutualistic relations between plants and fungi are very common. The fungus invades and lives in or among the cortex cells of the secondary roots. The association is called a **mycorrhiza**. The fungus helps the host plant absorb inorganic nitrogen and phosphorus from the soil. Some mycorrhizal fungi also secrete antibiotics which may help protect their host from invasion by parasitic fungi and bacteria. Many mushrooms are the spore-forming bodies of mycorrhizal fungi. The truffle is often found in oak forests because the fungus that produces it establishes mycorrhiza on oak roots.

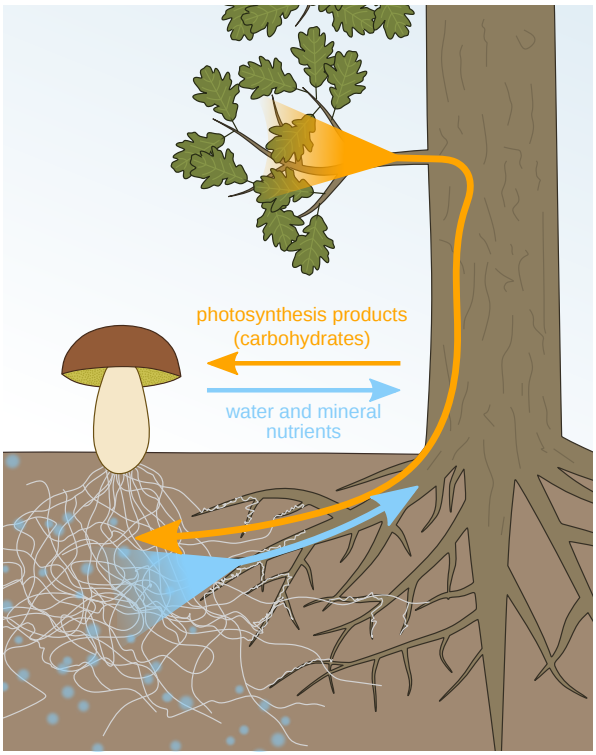


Figure 3.9.1: Mutualistic relations between plants and fungi are very common. The fungus helps the host plant absorb water, inorganic nitrogen, and phosphorus from the soil, and the plant provides sugar to the fungus. Nefronus, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

Endosymbiosis

Endosymbiosis is a **mutualistic** relationship between a host and an organism living within its body or cells.

The pea aphid and its endosymbiont

The pea aphid, *Acyrthosiphon pisum*, is an insect pest that sucks the juices from its host plant. However, plant sap is deficient in several essential amino acids. The pea aphid thrives nonetheless thanks to specialized cells within its body that contain the gamma proteobacterium, *Buchnera aphidicola*, that can live nowhere else. The genome of this obligate intracellular Gram-negative bacterium encodes a number of enzymes needed to complete the synthesis of the amino acids needed by its host. In return, the aphid's genome encodes enzymes needed by *Buchnera* to synthesize its lipopolysaccharide cell wall and has lost genes that might otherwise repel infection by Gram-negative bacteria.

Symbiotic nitrogen fixation

One of the most important examples of mutualism in the overall economy of the biosphere is the endosymbiotic relationship between certain nitrogen-fixing bacteria and their legume hosts. A large body of evidence supports the view that intracellular endosymbiotic relationships gave rise to eukaryotes with their mitochondria and chloroplasts.

Cleaning Symbiosis

The drawing shows the Nile crocodile opening its mouth to permit the Egyptian plover to feed on any leeches attached to its gums. Cleaning symbiosis is more common in fish.

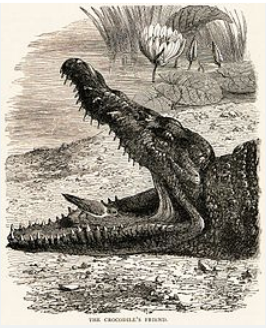


Figure 3.9.2: Cleaning symbiosis. Herodotus asserted that the trochilus bird, possibly a sandpiper, was able to enter the mouth of the Nile crocodile in what would now be called a cleaning symbiosis. Drawing by Henry Scherren, 1906

Commensalism

Commensalism means "at table together." It is used for symbiotic relationships in which one organism benefits, but the other doesn't seem to be affected, either positively or negatively.

Some examples:

- the remora and the shark. The dorsal fin of the remora (a bony fish) is modified into a sucker with which it forms a temporary attachment to the shark. When the shark feeds, the remora picks up scraps. The shark makes no attempt to prey on the remora.
- Some species of barnacles are found only as commensals on the jaws of whales. And there are other species of barnacles found only as commensals on those barnacles!
- Many of the bacteria live in our large intestine. They feed on food that we cannot digest and do not harm us.

Parasitism

A parasite is an organism that lives on or in the body of another organism (the host) from whose tissues it gets its nourishment, and to whom it does some damage. Animals are parasitized by viruses, bacteria, fungi, protozoans, flatworms (tapeworms and flukes), nematodes, insects (fleas, lice), and arachnids (mites). Plants are parasitized by viruses, bacteria, fungi, nematodes, and a few other plants.

Parasites damage their host in two major ways:

- consuming its tissues, e.g., a mosquito eats blood
- releasing toxins, for example, the bacteria *Tetanus bacilli* secrete tetanus toxin, which can be deadly.

The relationship between parasite and host varies along a spectrum that extends from "hit and run" parasites that live in or on their host for a brief period and then move on to another, with or without killing the first, to parasites that establish long-term, chronic infections. Both parasite and host must evolve to ensure the survival of both because if the parasite kills its host before it can move on, it destroys its habitat.

The "simplification" of Parasites

During the course of adapting to conditions in their host, parasites often lose structures and functions that were essential for their ancestors (and any free-living relatives). The tapeworm has no eyes, no digestive tract, and only vestiges of nervous, excretory, and muscular systems. While you may call them degenerate, these losses represent a gain in efficiency and improved specialization. What good would these structures be any way in the human intestine? On the other hand, the tapeworm produces hundreds of proglottids: egg-forming machines that improve the likelihood that the tapeworm will leave descendants that reach another host.

The Evolution of Symbiosis

It seems plausible that what begins as a parasitic relationship might over the course of time evolve into a mutualistic one as the two organisms evolve to minimize the damage to the host.

And there is some evidence for this. In 1966, K. W. Jeon discovered a culture of amoebas that had become infected with bacteria (60,00 to 150,000 per cell). The infection slowed their rate of growth and made them much more fragile. But five years later, the

amoebas still were infected but now no ill effects could be seen. Most interesting for our question, the amoebas — or at least their nuclei — had become dependent on the bacteria.

- When the nucleus was removed from an infected amoeba and replaced with one from an uninfected strain, the combination worked fine.
- But when the nucleus from an uninfected cell was replaced with one from an infected cell, the combination usually failed to survive.

Evidently, after 5 years, the nuclei had become dependent on a bacterial function (an enzyme produced by the bacteria but no longer by the host). What started as parasitism had evolved into mutualism (the bacteria could not be grown outside their host). But it doesn't always work like that. There are other examples where a mutualistic relationship seems to have evolved into a commensalistic or even parasitic one. Some parasitic fungi seem to have evolved from ancestors living in the mutualistic partnership of a lichen.

Some of the bacteria living in our large intestine supply us with vitamin K, thus evolving from commensalism to mutualism.

Mutually beneficial symbiotic relationships can lead to simplification as well. Some marine annelid worms have completely lost the digestive tract of their relatives (like the common earthworm). One species gets its nourishment from a large population of at least 5 different species of bacteria living underneath its outer skin. The most abundant of these are **chemoautotrophs** (using chemicals as an energy source) that manufacture food from carbon dioxide using the energy provided by oxidizing inorganic substances (H_2S, H_2) in the sediments in which the worm lives.

The nature of a symbiotic relationship can also change as circumstances change. Some fungi, bacteria, and protozoans that live harmlessly in most of us can cause **opportunistic infections** — that is become parasitic — in immunodeficient people, e.g., those with AIDS.

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CHAPTER OVERVIEW

4: Populations

4.1: Population Demographics and Dynamics

4.2: Population Growth and Regulation

4.3: Factors Limiting Population Growth

4.4: The Human Population

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4.1: Population Demographics and Dynamics

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

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

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 4.1.1).

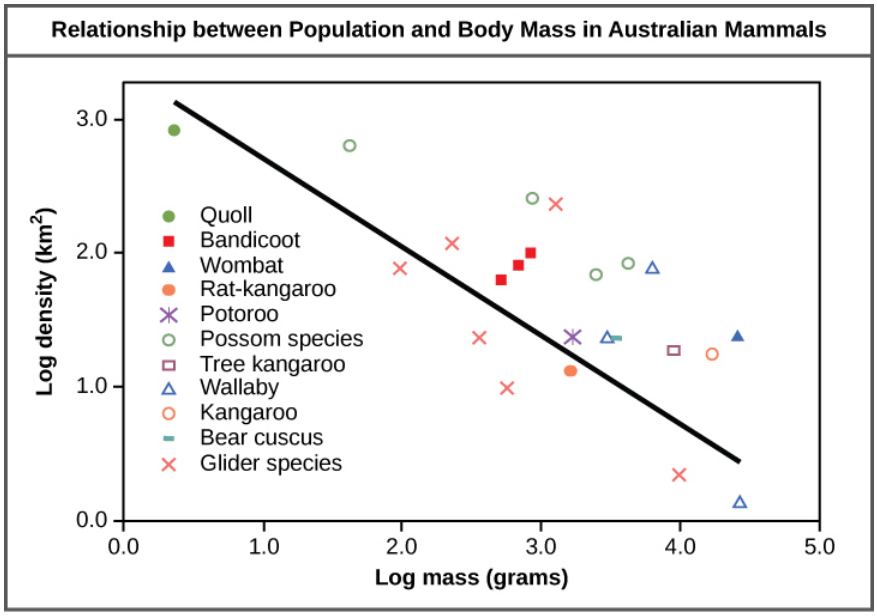


Figure 4.1.1. Australian mammals show a typical inverse relationship between population density and body size. As this graph shows, population density typically decreases with increasing body size. Why do you think this is the case?

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 square structure that is randomly located on the ground and used to count the number of individuals that lie within its

boundaries. To obtain an accurate count using this method, the square must be placed at random locations within the habitat enough times to produce an accurate estimate.

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

$$N = \frac{(\text{number marked first catch} \times \text{total number of second catch})}{\text{number marked second catch}} \tag{4.1.1}$$

Using our example, the equation would be:

$$\frac{(80 \times 100)}{20} = 400 \tag{4.1.2}$$

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

Species Distribution

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

Individuals within a population can be distributed at random, in groups, or equally spaced apart (more or less). These are known as **random, clumped, and uniform distribution patterns**, respectively (Figure 4.1.2). 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.

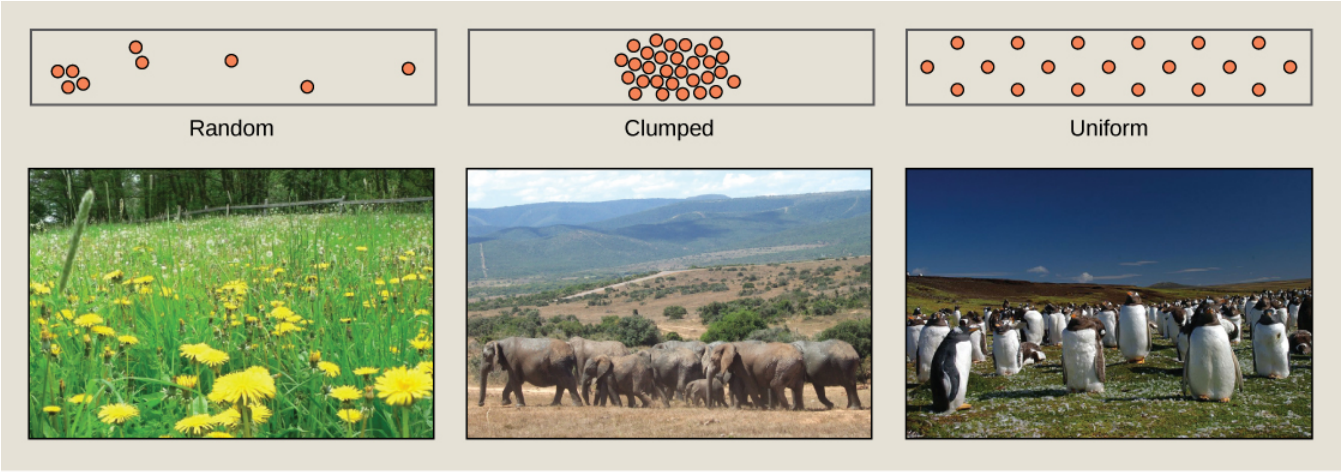


Figure 4.1.2. Species may have a random, clumped, or uniform distribution. Plants such as (a) dandelions with wind-dispersed seeds tend to be randomly distributed. Animals such as (b) elephants that travel in groups exhibit a clumped distribution. Territorial birds such as (c) penguins tend to have a 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)

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

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

Table 1: Life Table of Dall Mountain Sheep

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

Another tool used by population ecologists is a **survivorship curve**, which is a graph of the number of individuals surviving at each age interval versus time. These curves allow us to compare the life histories of different populations (Figure 4.1.3). 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.

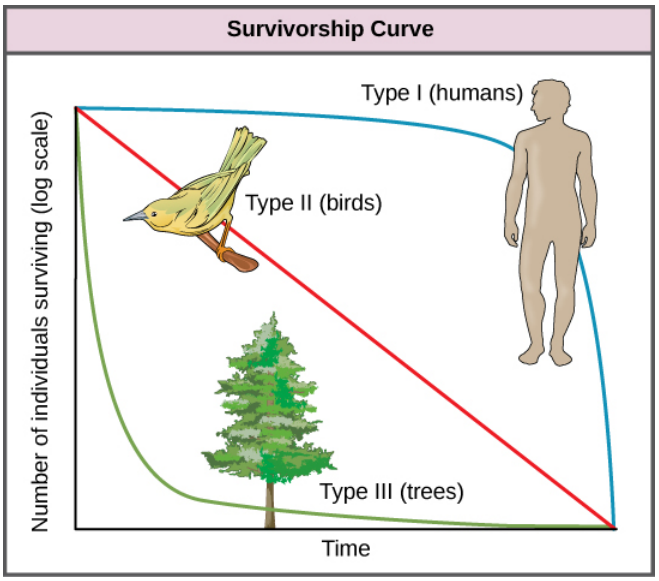


Figure 4.1.3. Survivorship curves show the distribution of individuals in a population according to age. Humans and most mammals have a Type I survivorship curve, because death primarily occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees 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.

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

Exponential Growth

Charles Darwin, in developing his theory of natural selection, was influenced by the English clergyman Thomas Malthus. Malthus published his book in 1798 stating that populations with abundant natural resources grow very rapidly. However, they limit further growth by depleting their resources. The early pattern of accelerating population size is called exponential growth (Figure 4.2.1).

The best example of exponential growth in organisms is seen in bacteria. Bacteria are prokaryotes that reproduce quickly, about an hour for many species. If 1000 bacteria are placed in a large flask with an abundant supply of nutrients (so the nutrients will not become quickly depleted), the number of bacteria will have doubled from 1000 to 2000 after just an hour. In another hour, each of the 2000 bacteria will divide, producing 4000 bacteria. After the third hour, there should be 8000 bacteria in the flask. The important concept of exponential growth is that the growth rate—the number of organisms added in each reproductive generation—is itself increasing; that is, the population size is increasing at a greater and greater rate. After 24 of these cycles, the population would have increased from 1000 to more than 16 billion bacteria. When the population size, *N*, is plotted over time, a J-shaped growth curve is produced (Figure 4.2.1).

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

Logistic Growth

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

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 4.2.1). This population size, which is determined by the maximum population size that a particular environment can sustain, is called the **carrying capacity**, symbolized as *K*. In real populations, a growing population often overshoots its carrying capacity and the death rate increases beyond the birth rate causing the population size to decline back to the carrying capacity or below it. Most populations usually fluctuate around the carrying capacity in an undulating fashion rather than existing right at it.

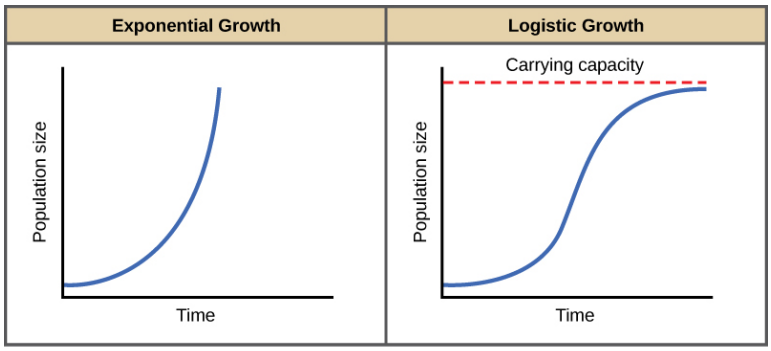


Figure 4.2.1. When resources are unlimited, populations exhibit (a) exponential growth, shown in a J-shaped curve. When resources are limited, populations exhibit (b) logistic growth. In logistic growth, population expansion decreases as resources become scarce, and it levels off when the carrying capacity of the environment is reached. The logistic growth curve is S-shaped.

A graph of logistic growth yields the S-shaped curve (Figure 4.2.1). It is a more realistic model of population growth than exponential growth. There are three different sections to an S-shaped curve. Initially, growth is exponential because there are few individuals and ample resources available. Then, as resources begin to become limited, the growth rate decreases. Finally, the growth rate levels off at the carrying capacity of the environment, with little change in population number over time.

Examples of Logistic Growth

Yeast, a unicellular fungus used to make bread and alcoholic beverages, exhibits the classical S-shaped curve when grown in a test tube (Figure 4.2.2a). Its growth levels off as the population depletes the nutrients that are necessary for its growth. In the real world, however, there are variations to this idealized curve. Examples in wild populations include sheep and harbor seals (Figure 4.2.2b). In both examples, the population size exceeds the carrying capacity for short periods of time and then falls below the carrying capacity afterwards. This fluctuation in population size continues to occur as the population oscillates around its carrying capacity. Still, even with this oscillation the logistic model is confirmed.

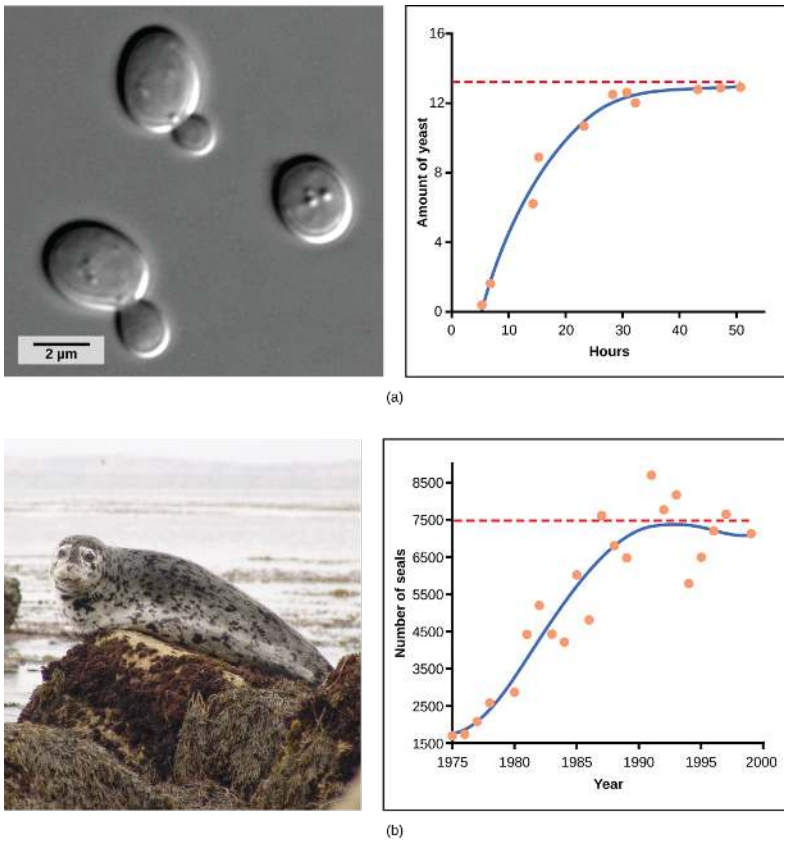


Figure 4.2.2. (a) Yeast grown in ideal conditions in a test tube shows a classical S-shaped logistic growth curve, whereas (b) a natural population of seals shows real-world fluctuation. The yeast is visualized using differential interference contrast light micrography. (credit a: scale-bar data from Matt Russell)

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.

Why Did the Woolly Mammoth Go Extinct?

Most populations of woolly mammoths went extinct about 10,000 years ago, soon after paleontologists believe humans began to colonize North America and northern Eurasia (Figure 4.2.3). A mammoth population survived on Wrangel Island, in the East Siberian Sea, and was isolated from human contact until as recently as 1700 BC. We know a lot about these animals from carcasses found frozen in the ice of Siberia and other northern regions.

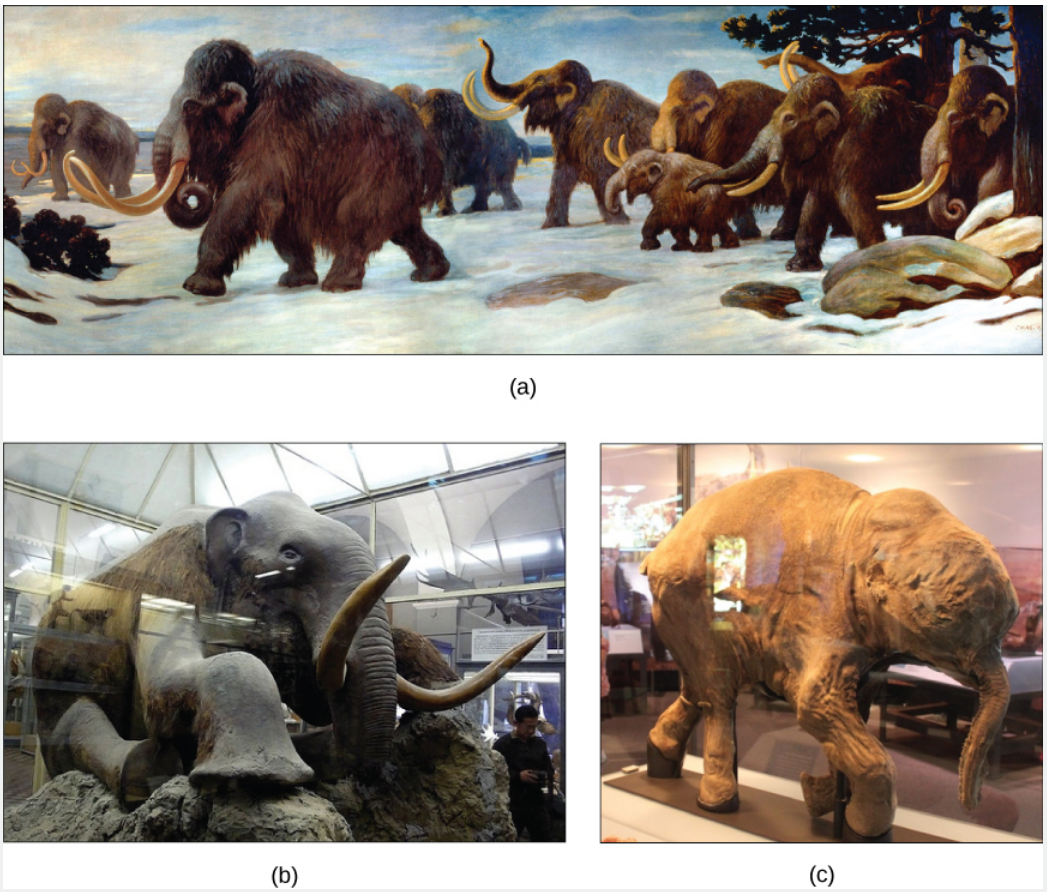


Figure 4.2.3. The three images include: (a) 1916 mural of a mammoth herd from the American Museum of Natural History, (b) the only stuffed mammoth in the world is in the Museum of Zoology located in St. Petersburg, Russia, and (c) a one-month-old baby mammoth, named Lyuba, discovered in Siberia in 2007. (credit a: modification of work by Charles R. Knight; credit b: modification of work by "Tanapon"/Flickr; credit c: modification of work by Matt Howry)

It is commonly thought that climate change and human hunting led to their extinction. A 2008 study estimated that climate change reduced the mammoth's range from 3,000,000 square miles 42,000 years ago to 310,000 square miles 6,000 years ago.[2] Through archaeological evidence of kill sites, it is also well documented that humans hunted these animals. A 2012 study concluded that no single factor was exclusively responsible for the extinction of these magnificent creatures.[3] In addition to climate change and reduction of habitat, scientists demonstrated another important factor in the mammoth's extinction was the migration of human hunters across the Bering Strait to North America during the last ice age 20,000 years ago.

The maintenance of stable populations was and is very complex, with many interacting factors determining the outcome. It is important to remember that humans are also part of nature. Once we contributed to a species' decline using primitive hunting technology only.

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.

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4.3: Factors Limiting Population Growth

Recall previously that we defined density as the number of individuals per unit area. In nature, a population that is introduced to a new environment or is rebounding from a catastrophic decline in numbers may grow exponentially for a while because density is low and resources are not limiting. Eventually, one or more environmental factors will limit its population growth rate as the population size approaches the carrying capacity and density increases. Example: imagine that in an effort to preserve elk, a population of 20 individuals is introduced to a previously unoccupied island that's 200 km^2 in size. The population density of elk on this island is 0.1 elk/km^2 (or 10 km^2 for each individual elk). As this population grows (depending on its per capita rate of increase), the number of individuals increases but the amount of space does not so density increases. Suppose that 10 years later, the elk population has grown to 800 individuals, density = 4 elk/ km^2 (or 0.25 km^2 for each individual). The population growth rate will be limited by various factors in the environment. For example, birth rates may decrease due to limited food or death rate increase due to rapid spread of disease as individuals encounter one another more often. This impact on birth and death rate in turn influences the per capita rate of increase and how the population size changes with changes in the environment. When birth and death rates of a population change as the density of the population changes, the rates are said to be density-dependentand the environmental factors that affect birth and death rates are known as **density-dependent factors**. In other cases, populations are held in check by factors that are not related to the density of the population and are called **density-independent** factors and influence population size regardless of population density. Conservation biologists want to understand both types because this helps them manage populations and prevent extinction or overpopulation.

The density of a population can enhance or diminish the impact of *density-dependent* factors. Most density-dependent factors are *biological in nature* (biotic), and include such things as predation, inter- and intraspecific competition for food and mates, accumulation of waste, and diseases such as those caused by parasites. Usually, higher population density results in higher death rates and lower birth rates. For example, as a population increases in size food becomes scarcer and some individuals will die from starvation meaning that the death rate from starvation increases as population size increases. Also as food becomes scarcer, birth rates decrease due to fewer available resources for the mother meaning that the birth rate decreases as population size increases. For density-dependent factors, there is a feedback loop between population density and the density-dependent factor.

Two examples of density-dependent regulation are shown in Figure 4.3.1. First one is showing results from a study focusing on the giant intestinal roundworm (*Ascaris lumbricoides*), a parasite that infects humans and other mammals. Denser populations of the parasite exhibited lower fecundity (number of eggs per female). One possible explanation for this is that females would be smaller in more dense populations because of limited resources and smaller females produce fewer eggs.

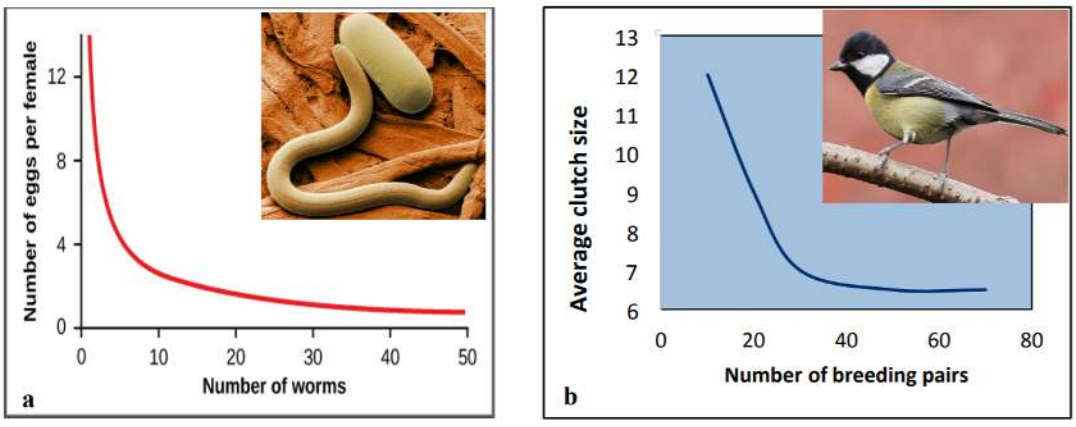


Figure 4.3.1: (a) Graph of number of eggs per female (fecundity), as a function of population size. In this population of roundworms, fecundity (number of eggs) decreases with population density. (b) Graph of clutch size (number of eggs per "litter") of the great tits bird as a function of population size (breeding pairs). Again, clutch size decreases as population density increases. (Photo credits: Worm image from Wikimedia commons, public domain image; bird image from Wikimedia commons, photo by Francis C. Franklin / CC-BY-SA-3.0)

Density-independent birth rates and death rates do NOT depend on population size; these factors are independent of, or not influenced by, population density. Many factors influence population size regardless of the population density, including weather extremes, natural disasters (earthquakes, hurricanes, tornadoes, tsunamis, etc.), pollution and other physical/abiotic factors. For example, an individual deer may be killed in a forest fire regardless of how many deer happen to be in the forest. The forest fire is

not responding to deer population size. As the weather grows cooler in the winter, many insects die from the cold. The change in weather does not depend on whether there is a population size of 100 mosquitoes or 100,000 mosquitoes, most mosquitoes will die from the cold regardless of the population size and the weather will change irrespective of mosquito population density. Looking at the growth curve of such a population would show something like an exponential growth followed by a rapid decline rather than levelling off (Figure 4.3.2).

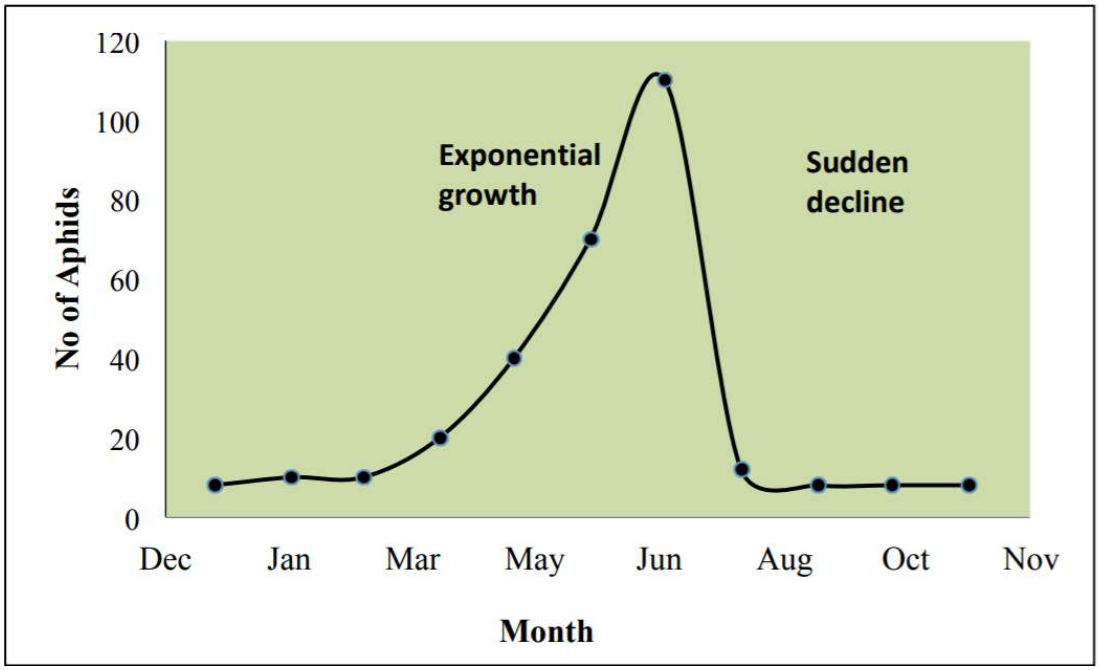


Figure 4.3.2: Weather change acting as a density-independent factor limiting aphid population growth. This insect undergoes exponential growth in the early spring and then rapidly die off when the weather turns hot and dry in the summer

In real-life situations, density-dependent and independent factors interact. For example, a devastating earthquake occurred in Haiti in 2010. This earthquake was a natural geologic event that caused a high human death toll from this *density-independent* event. Then there were high densities of people in refugee camps and the high density caused disease to spread quickly, representing a *density-dependent* death rate.

Q: Can you think of other density-dependent (biological) and density-independent (abiotic) population limiting factors?

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4.4: 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 its use of resources are growing rapidly, to the extent that some worry about the ability of Earth's environment to sustain its human population. Long-term exponential growth carries with it the potential risks of famine, disease, and large-scale death, as well as social consequences of crowding, such as increased crime.

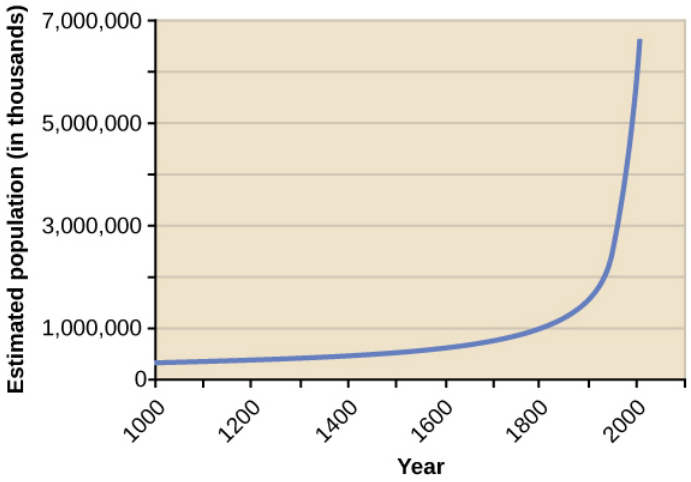


Figure 4.4.1. Human population growth since 1000 AD is exponential.

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.

Human Population Growth

The fundamental cause of the acceleration of the growth rate for humans in the past 200 years has been the reduced death rate due to changes in public health and sanitation. Clean drinking water and proper sewage disposal has drastically improved health in developed nations. Also, medical innovations such as the use of antibiotics and vaccines have decreased the ability of infectious diseases to limit human population growth. In the past, diseases such as the bubonic plague of the fourteenth century killed between 30 and 60 percent of Europe's population and reduced the overall world population by as many as one hundred million people. Naturally, infectious disease continues to have an impact on human population growth, especially in poorer nations. 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.

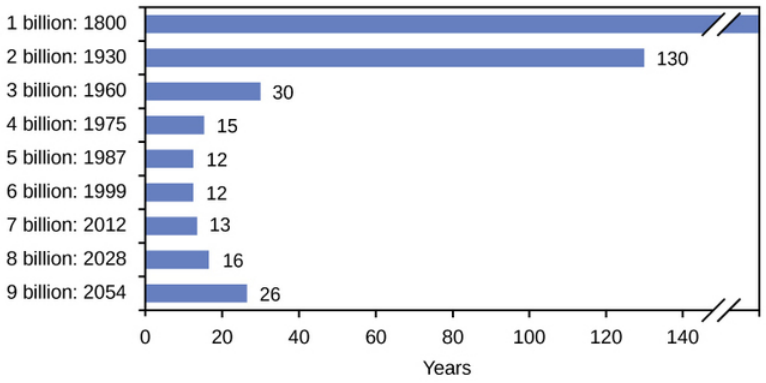
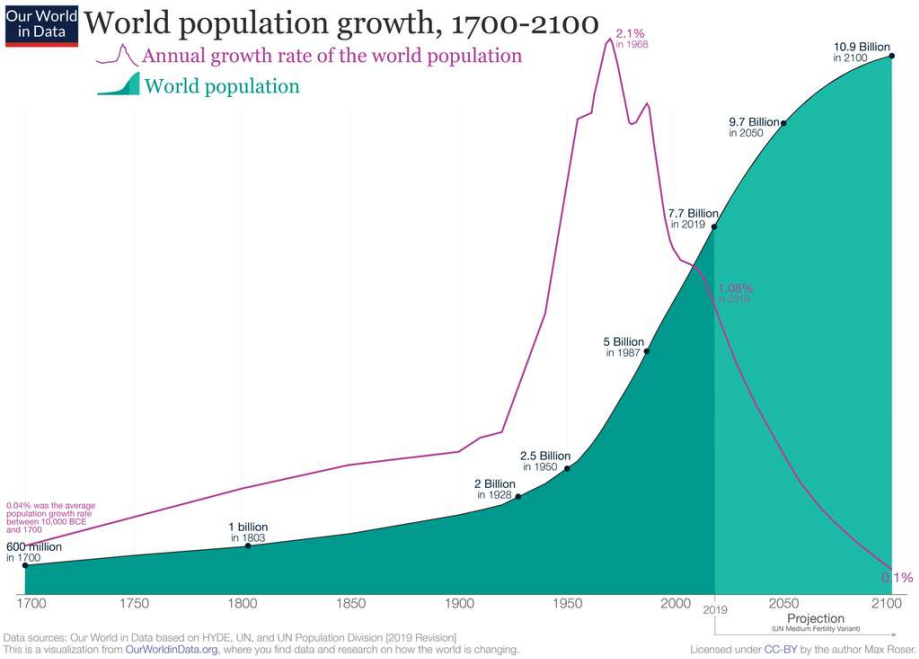


Figure 4.4.2. The time between the addition of each billion human beings to Earth decreases over time. (credit: modification of work by Ryan T. Cragun)

Technological advances of the industrial age have also supported population growth through urbanization and advances in agriculture. These advances in technology were possible, in part, due to the exploitation of fossil fuels.



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Even as the rate of growth has dropped since the 1960s and 1970s, the overall population continues to grow.

What is the population of the world?

Current World Population- click on the link to see the estimated current population.

Was this a higher or lower number then you thought?

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 4.4.3).

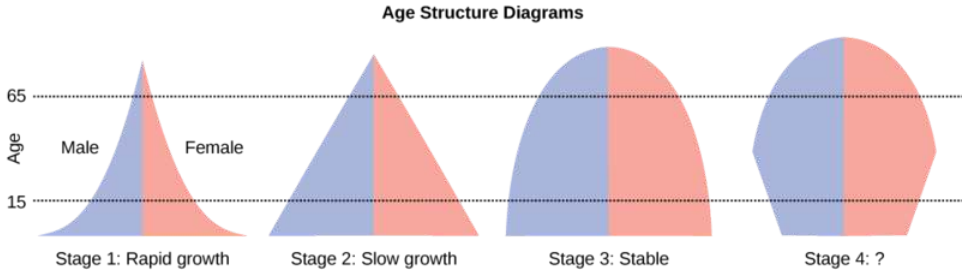


Figure 4.4.3. Typical age structure diagrams are shown. The rapid growth diagram narrows to a point, indicating that the number of individuals decreases rapidly with age. In the slow growth model, the number of individuals decreases steadily with age. Stable population diagrams are rounded on the top, showing that the number of individuals per age group decreases gradually, and then increases for the older part of the population.

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 4.4.4, with the highest rates tending to be in the less economically developed countries of Africa and Asia.

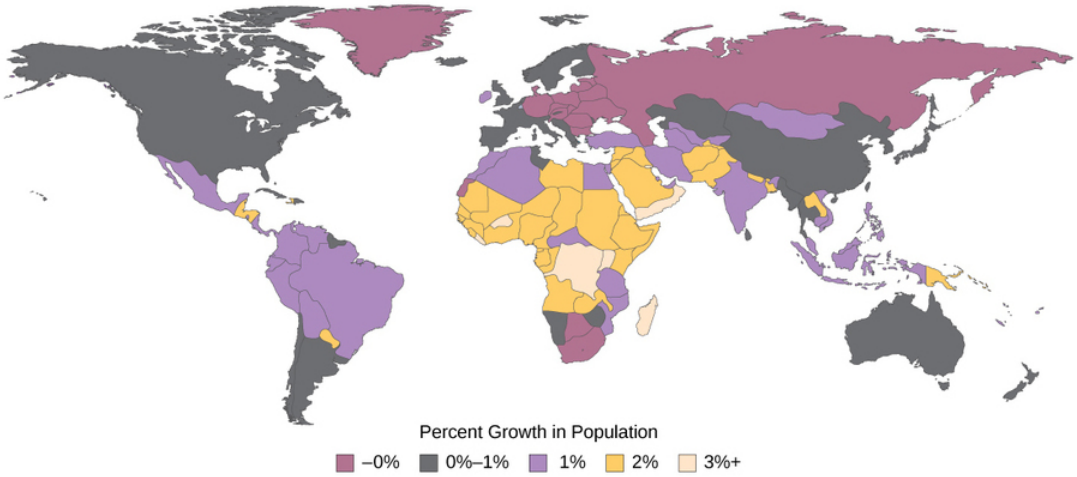


Figure 4.4.4. The percent growth rate of population in different countries is shown. Notice that the highest growth is occurring in less economically developed countries in Africa and Asia.

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 Paul R. Ehrlich wrote,

> *"The battle to feed all of humanity is over. In the 1970s hundreds of millions of people will starve to death in spite of any crash programs embarked upon now. At this late date nothing can prevent a substantial increase in the world death rate."*

While these predictions obviously didn't bear fruit, the laws of exponential population growth are still in effect, and unchecked human population growth cannot continue indefinitely. Efforts to moderate population control led to the one-child policy in China, which imposes fines on urban couples who have more than one child. Due to the fact that some couples wish to have a male heir, many Chinese couples continue to have more than one child. The effectiveness of the policy in limiting overall population growth is controversial, as is the policy itself. Moreover, there are stories of female infanticide having occurred in some of the more rural areas of the country. 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. The United Nations estimates the future world population size to be 11.2 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, despite the overwhelming scientific evidence. Thus, we enter the future with considerable uncertainty about our ability to curb human population growth and protect our environment to maintain the carrying capacity for the human species.

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- Current world population graphs and estimates by Kevin Raskoff, Monterey Peninsula College.

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CHAPTER OVERVIEW

5: Biodiversity and Conservation

5.1: Introduction to Biodiversity
5.2: Importance of Biodiversity
5.3: Threats to Biodiversity
5.4: Alpha, Beta, and Gamma Diversity
5.5: Population Diversity
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5.1: Introduction to Biodiversity

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

Biologists name, group, and classify organisms based on similarities in genetics and morphology. This branch of biological science is known as **taxonomy**. Taxonomists group organisms into categories that range from very broad to very specific (Figure 5.1.1). The broadest category is called **domain** and the most specific is **species** (notice the similarities between the words *specific* and *species*). Currently, taxonomists recognize three domains: Bacteria, Archaea, and Eukarya. All life forms are classified within these three domains.

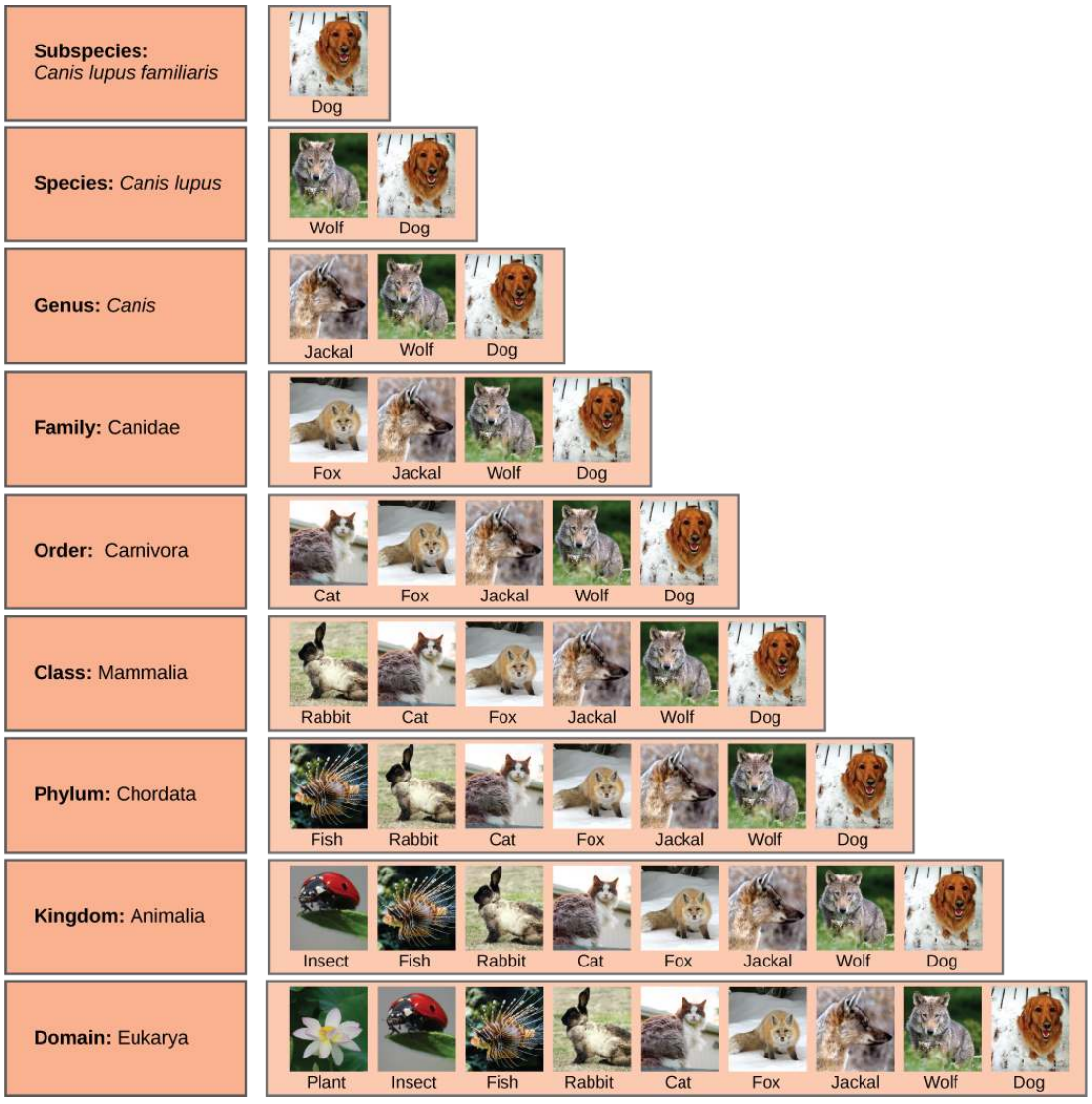


Figure 5.1.1. This illustration shows the taxonomic groups, in sequence, with examples. *This illustration by OpenStax is licensed under CC BY 4.0*

Domain Bacteria

Domain Bacteria includes prokaryotic, unicellular organisms (Figure 5.1.2). They are incredibly abundant and found in nearly every imaginable type of habitat, including your body. While many people view bacteria only as disease-causing organisms, most species are actually either benign or beneficial to humans. While it is true that some bacteria may cause disease in people, this is more the exception than the rule.

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

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

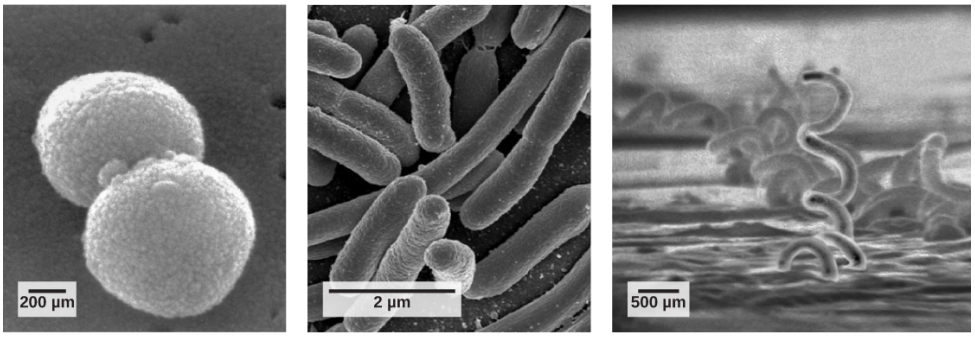


Figure 5.1.2. Many prokaryotes fall into three basic categories based on their shape: (a) cocci, or spherical; (b) bacilli, or rod-shaped; and (c) spirilla, or spiral-shaped. (credit a: modification of work by Janice Haney Carr, Dr. Richard Facklam, CDC; credit c: modification of work by Dr. David Cox, CDC; scale-bar data from Matt Russell). *This figure by OpenStax is licensed under CC BY 4.0*

Domain Archaea

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

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

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

Domain Eukarya

This domain is most familiar to use because it includes humans and other animals, along with plants, fungi, and a lesser-known group, the protists. Unlike the other domains, **Domain Eukarya**contains multicellular organisms, in addition to unicellular species. The domain is characterized by the presence of eukaryotic cells. For this domain, you will be introduced to several of its kingdoms. **Kingdom** is the taxonomic grouping immediately below domain (see Figure 5.1.1).

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



Figure 5.1.3. The (a) familiar mushroom is only one type of fungus. The brightly colored fruiting bodies of this (b) coral fungus are displayed. This (c) electron micrograph shows the spore-bearing structures of Aspergillus, a type of toxic fungi found mostly in soil and plants. (credit a: modification of work by Chris Wee; credit b: modification of work by Cory Zanker; credit c: modification of work by Janice Haney Carr, Robert Simmons, CDC; scale-bar data from Matt Russell). *This work by OpenStax is licensed under CC BY 4.0.*

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

Protists refer to a highly disparate group that was formerly its own kingdom until recent genetic analysis indicated that it should be split in to many kingdoms (Figure 5.1.4). As a group, protists are very diverse and include unicellular, multicellular, heterotrophic, and autotrophic organisms. The term 'protist' was used as a catchall for any eukaryote that was neither animal, plant, or fungus. Examples of protists include macroalgae such as kelps and seaweeds, microalgae such as diatoms and dinoflagellates, and important disease-causing microbes such as *Plasmodium*, the parasite that causes malaria. Sadly, malaria kills hundreds of thousands of people every year.

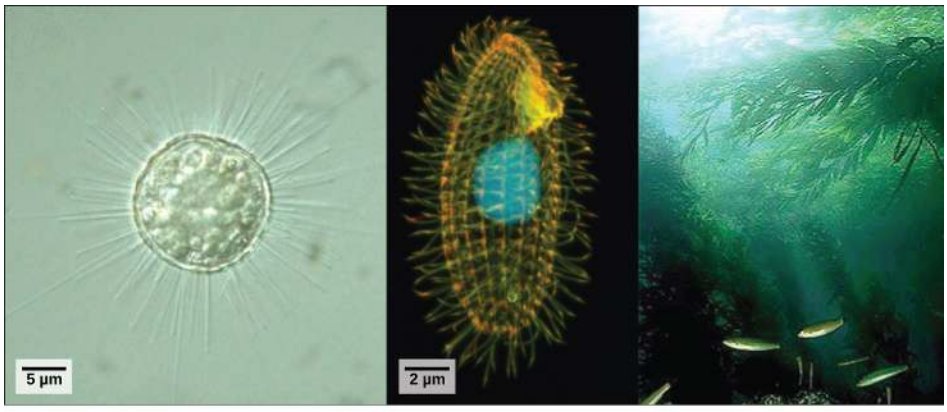


Figure 5.1.4. Protists range from the microscopic, single-celled (a) *Acanthocystis turfacea and the (b) ciliate Tetrahymena thermophilato the enormous, multicellular (c) kelps (Chromalveolata) that extend for hundreds of feet in underwater "forests." (credit a: modification of work by Yuiuji Tsukii; credit b: modification of work by Richard Robinson, Public Library of Science; credit c: modification of work by Kip Evans, NOAA; scale-bar data from Matt Russell). This work by OpenStax is licensed under CC BY 4.0*

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

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5.2: Importance of Biodiversity

Biodiversity is a broad term for biological variety, and it can be measured at a number of organizational levels. Traditionally, ecologists have measured biodiversity by taking into account both the number of species and the number of individuals in each of those species. However, biologists are using measures of biodiversity at several levels of biological organization (including genes, populations, and ecosystems) to help focus efforts to preserve the biologically and technologically important elements of biodiversity.

When biodiversity loss through extinction is thought of as the loss of the passenger pigeon, the dodo, or, even, the woolly mammoth there seems to be no reason to care about it because these events happened long ago. How is the loss practically important for the welfare of the human species? Would these species have made our lives any better? From the perspective of evolution and ecology, the loss of a particular individual species, with some exceptions, may seem unimportant, but the current accelerated extinction rate means the loss of tens of thousands of species within our lifetimes. Much of this loss is occurring in tropical rainforests like the one pictured in Figure 5.2.1, which are especially high-diversity ecosystems that are being cleared for timber and agriculture. This 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 improve human health.



Figure 5.2.1: This tropical lowland rainforest in Madagascar is an example of a high biodiversity habitat. This particular location is protected within a national forest, yet only 10 percent of the original coastal lowland forest remains, and research suggests half the original biodiversity has been lost. (credit: Frank Vassen)

Biologists recognize that human populations are embedded in ecosystems and are dependent on them, just as is every other species on the planet. Agriculture began after early hunter-gatherer societies first settled in one place and heavily modified their immediate environment: the ecosystem in which they existed. This cultural transition has made it difficult for humans to recognize their dependence on living things other than crops and domesticated animals on the planet. Today our technology smoothes out the extremes of existence and allows many of us to live longer, more comfortable lives, but ultimately the human species cannot exist without its surrounding ecosystems. Our ecosystems provide our food. This includes living plants that grow in soil ecosystems and the animals that eat these plants (or other animals) as well as photosynthetic organisms in the oceans and the other organisms that eat them. Our ecosystems have provided and will provide many of the medications that maintain our health, which are commonly made from compounds found in living organisms. Ecosystems provide our clean water, which is held in lake and river ecosystems or passes through terrestrial ecosystems on its way into groundwater.

Types of Biodiversity

A common meaning of biodiversity is simply the number of species in a location or on Earth; for example, the American Ornithologists' Union lists 2078 species of birds in North and Central America. This is one measure of the bird biodiversity on the continent. More sophisticated measures of diversity take into account the relative abundances of species. For example, a forest with 10 equally common species of trees is more diverse than a forest that has 10 species of trees wherein just one of those species makes up 95 percent of the trees rather than them being equally distributed. Biologists have also identified alternate measures of biodiversity, some of which are important in planning how to preserve biodiversity.

Genetic Diversity

Genetic diversity is one concept of biodiversity. Genetic diversity (or variation) is the raw material for 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 look alike and have similar ecologies. The genus with the greatest potential for subsequent evolution is the most genetically diverse one.

Most genes code for proteins, which in turn carry out the metabolic processes that keep organisms alive and reproducing. Genetic diversity can also be conceived of as chemical diversity in that species with different genetic makeups produce different assortments of chemicals in their cells (proteins as well as the products and byproducts of metabolism). This chemical diversity is important for humans because of the potential uses for these chemicals, such as medications. For example, the drug eptifibatide is derived from rattlesnake venom and is used to prevent heart attacks in individuals with certain heart conditions.

At present, it is far cheaper to discover compounds made by an organism than to imagine them and then synthesize them in a laboratory. Chemical diversity is one way to measure diversity that is important to human health and welfare. Through selective breeding, humans have domesticated animals, plants, and fungi, but even this diversity is suffering losses because of market forces and increasing globalism in human agriculture and migration. For example, international seed companies produce only a very few varieties of a given crop and provide incentives around the world for farmers to buy these few varieties while abandoning their traditional varieties, which are far more diverse. The human population depends on crop diversity directly as a stable food source, and its decline is troubling to biologists and agricultural scientists.

Species Diversity

The species diversity is what most people first think of when they ponder the idea of biodiversity: it is the number of different species in an area. This is also known as the **species richness**. Despite considerable effort, knowledge of the species that inhabit the planet is limited. A recent estimate suggests that the eukaryote species for which science has names, about 1.5 million species, account for less than 20 percent of the total number of eukaryote species present on the planet (8.7 million species, by one estimate). Estimates of the number of prokaryotic species are largely guesses, but biologists agree that science has only just begun to catalog their diversity. Even with what is known, there is no centralized repository of names or samples of the described species; therefore, there is no way to be sure that the 1.5 million descriptions is an accurate number. It is a best guess based on the opinions of experts on different taxonomic groups. Given that Earth is losing species at an accelerating pace, science knows little about what is being lost. Table 5.2.1 presents recent estimates of biodiversity in different groups.

Table 5.2.1: Estimated Numbers of Described and Predicted species

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

Table 5.2.1***:*** *This table shows the estimated number of species by taxonomic group—including both described (named and studied) and predicted (yet to be named) species.*

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

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

Ecosystem Diversity

It is also useful to define ecosystem (or habitat) diversity: the number of different ecosystems on Earth or in a geographical area. 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 the 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 (Figure 5.2.2). Prairies once spanned central North America from the boreal forest in northern Canada down into Mexico. They are now all but gone, replaced by crop fields, pasture lands, and suburban sprawl. Many of the species survive, but the hugely productive ecosystem that was responsible for creating our most productive agricultural soils is now gone. As a consequence, their soils are now being depleted unless they are maintained artificially at greater expense. The decline in soil productivity occurs because the interactions in the original ecosystem have been lost; this was a far more important loss than the relatively few species that were driven extinct when the prairie ecosystem was destroyed.

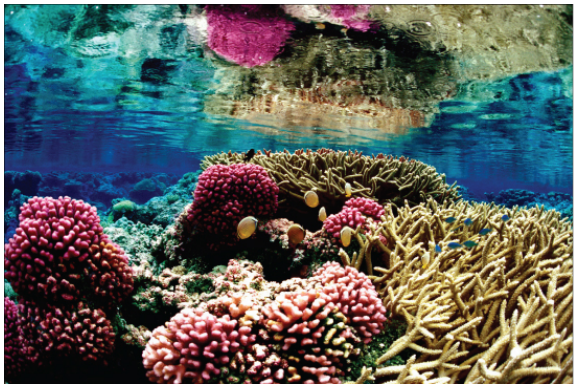
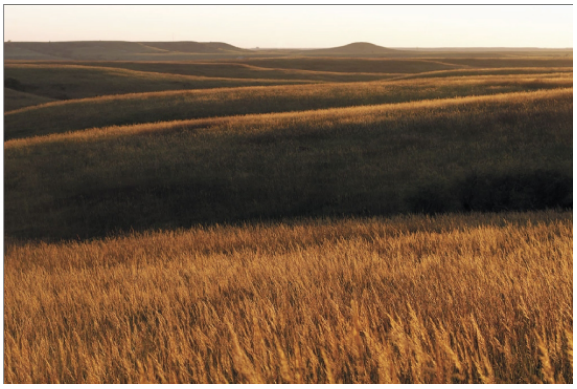



Figure 5.2.2: The variety of ecosystems on Earth—from coral reef to prairie—enables a great diversity of species to exist. (credit "coral reef": modification of work by Jim Maragos, USFWS; credit: "prairie": modification of work by Jim Minnerath, USFWS)

Richness and Evenness = Biodiversity

In ecology, species richness refers to the number of different species in an ecosystem, while species evenness describes the relative abundance of each species. High richness means many different species are present, and high evenness means the species are represented by roughly equal numbers of individuals. It is the mathematical combination of richness and evenness that equals the concept of biodiversity. While both are components of biodiversity, they are distinct concepts. A community can have high species richness but low evenness, meaning many different species are present, but some are very dominant. Similarly, a community can have low richness but high evenness, meaning fewer species are present, but they are more equally represented.

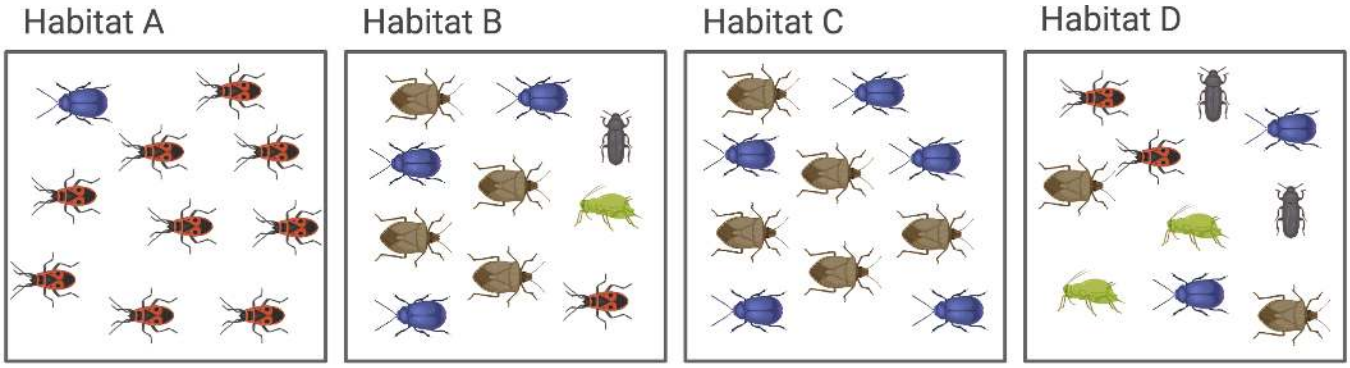


Figure created by L Gerhart-Barley with biorender.com. BIS 2B: Introduction to Biology - Ecology and Evolution is shared under a CC BY-SA 4.0 license and was authored, remixed, and/or curated by Laci M. Gerhart-Barley.

Look the the figure above. In Habitat A we have two species (blue and red), and in Habitat C we also have two species (blue and brown). The species richness is the same in both habitats, but would it seem the same if we looked at the beetles? Habitat A is dominated by the red beetles, while in Habitat C they are in equal numbers. Which area would be more biodiverse? The answer is habitat C. Because the species are more even in their abundance, the area would be more diverse than habitat A.

Patterns of Biodiversity

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

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

CAREER IN ACTION: Biogeography

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

There are three main fields of study under the heading of biogeography: ecological biogeography, historical biogeography (called paleobiogeography), and conservation biogeography. Ecological biogeography studies the current factors affecting the distribution of plants and animals. Historical biogeography, as the name implies, studies the past distribution of species. Conservation biogeography, on the other hand, is focused on the protection and restoration of species based upon the known historical and current ecological information. Each of these fields considers both zoogeography and phytogeography—the past and present distribution of animals and plants.

One of the oldest observed patterns in ecology is that biodiversity in almost every taxonomic group of organism increases as latitude declines. In other words, biodiversity increases closer to the equator (Figure 5.2.3).

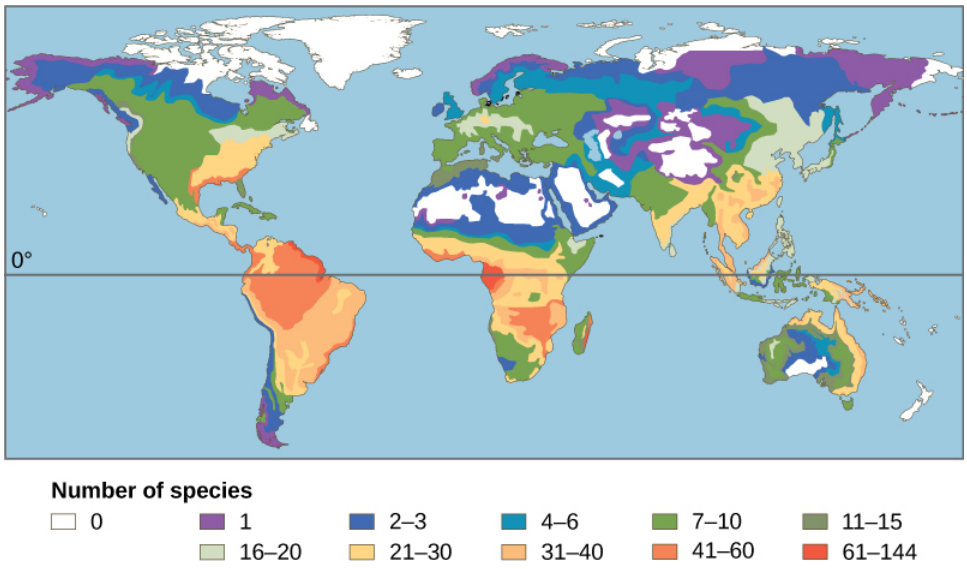


Figure 5.2.3: This map illustrates the number of amphibian species across the globe and shows the trend toward higher biodiversity at lower latitudes. A similar pattern is observed for most taxonomic groups.

It is not yet clear why biodiversity increases closer to the equator, but hypotheses include the greater age of the ecosystems in the tropics versus temperate regions, which were largely devoid of life or drastically impoverished during the last ice age. The greater age provides more time for speciation. Another possible explanation is the greater energy the tropics receive from the sun versus the lesser energy input in temperate and polar regions. But scientists have not been able to explain how greater energy input could translate into more species. The complexity of tropical ecosystems may promote speciation by increasing the habitat heterogeneity, or number of ecological niches, in the tropics relative to higher latitudes. The greater heterogeneity 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 and this stability might promote speciation.

Regardless of the mechanisms, it is certainly true that biodiversity is greatest in the tropics. The number of endemic species is higher in the tropics. The tropics also contain more biodiversity hotspots. At the same time, our knowledge of the species living in the tropics is lowest and because of recent, heavy human activity the potential for biodiversity loss is greatest.

Importance of Biodiversity

Loss of biodiversity eventually threatens other species we do not impact directly because of their interconnectedness; as species disappear from an ecosystem other species are threatened by the changes in available resources. Biodiversity is important to the survival and welfare of human populations because it has impacts on our health and our ability to feed ourselves through agriculture and harvesting populations of wild animals.

Human Health

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

Modern pharmaceutical science also recognizes the importance of these plant compounds. Examples of significant medicines derived from plant compounds include aspirin, codeine, digoxin, atropine, and vincristine (Figure 5.2.4). Many medications were

once derived from plant extracts but are now synthesized. It is estimated that, at one time, 25 percent of modern drugs contained at least one plant extract. That number has probably decreased to about 10 percent as natural plant ingredients are replaced by synthetic versions of the plant compounds. Antibiotics, which are responsible for extraordinary improvements in health and lifespans in developed countries, are compounds largely derived from fungi and bacteria.



Figure 5.2.4: 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 medications improve people's lives. Pharmaceutical companies are actively looking for new natural compounds that can function as medicines. It is estimated that one third of pharmaceutical research and development is spent on natural compounds and that about 35 percent of new drugs brought to market between 1981 and 2002 were from natural compounds.

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

Agricultural

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

Potatoes are only one example of agricultural diversity. Every plant, animal, and fungus that has been cultivated by humans has been bred from original wild ancestor species into diverse varieties arising from the demands for food value, adaptation to growing conditions, and resistance to pests. The potato demonstrates a well-known example of the risks of low crop diversity: during the tragic Irish potato famine (1845–1852 AD), the single potato variety grown in Ireland became susceptible to a potato blight—wiping out the crop. The loss of the crop led to famine, death, and mass emigration. Resistance to disease is a chief benefit to maintaining crop biodiversity and lack of diversity in contemporary crop species carries similar risks. Seed companies, which are the source of most crop varieties in developed countries, must continually breed new varieties to keep up with evolving pest

organisms. These same seed companies, however, have participated in the decline of the number of varieties available as they focus on selling fewer varieties in more areas of the world replacing traditional local varieties.

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

Since the 1920s, government agriculture departments have maintained seed banks of crop varieties as a way to maintain crop diversity. This system has flaws because over time seed varieties are lost through accidents and there is no way to replace them. In 2008, the Svalbard Global seed Vault, located on Spitsbergen island, Norway, (Figure 5.2.5) began storing seeds from around the world as a backup system to the regional seed banks. If a regional seed bank stores varieties in Svalbard, losses can be replaced from Svalbard should something happen to the regional seeds. The Svalbard seed vault is deep into the rock of the arctic island. Conditions within the vault are maintained at ideal temperature and humidity for seed survival, but the deep underground location of the vault in the arctic means that failure of the vault's systems will not compromise the climatic conditions inside the vault.

ART CONNECTION



Figure 5.2.5: The Svalbard Global Seed Vault is a storage facility for seeds of Earth's diverse crops. (credit: Mari Tefre, Svalbard Global Seed Vault)

The Svalbard seed vault is located on Spitsbergen island in Norway, which has an arctic climate. Why might an arctic climate be good for seed storage?

Although crops are largely under our control, our ability to grow them is dependent on the biodiversity of the ecosystems in which they are grown. That biodiversity creates the conditions under which crops are able to grow through what are known as ecosystem services—valuable conditions or processes that are carried out by an ecosystem. Crops are not grown, for the most part, in built environments. They are grown in soil. Although some agricultural soils are rendered sterile using controversial pesticide treatments, most contain a huge diversity of organisms that maintain nutrient cycles—breaking down organic matter into nutrient compounds that crops need for growth. These organisms also maintain soil texture that affects water and oxygen dynamics in the soil that are necessary for plant growth. Replacing the work of these organisms in forming arable soil is not practically possible. These kinds of processes are called ecosystem services. They occur within ecosystems, such as soil ecosystems, as a result of the diverse metabolic activities of the organisms living there, but they provide benefits to human food production, drinking water availability, and breathable air.

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

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

Wild Food Sources

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

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

Summary

Biodiversity exists at multiple levels of organization, and is measured in different ways depending on the goals of those taking the measurements. These include numbers of species, genetic diversity, chemical diversity, and ecosystem diversity. 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 eukaryotic 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.

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 are expected to be discovered in nature. Loss of biodiversity will impact the number of pharmaceuticals available to humans. Biodiversity may provide important psychological benefits 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 are being managed for sustainability. Fisheries' ability to provide protein to human populations is threatened when extinction occurs.

Art Connections

Figure 5.2.5: The Svalbard seed vault is located on Spitsbergen island in Norway, which has an arctic climate. Why might an arctic climate be good for seed storage?

Answer

The ground is permanently frozen so the seeds will keep, even if the electricity fails.

Footnotes

1. 1 International Institute for Species Exploration (IISE), *2011 State of Observed Species (SOS)*. Tempe, AZ: IISE, 2011. Accessed May, 20, 2012. species.asu.edu/SOS.

Glossary

biodiversity
: the variety of a biological system, typically conceived as the number of species, but also applying to genes, biochemistry, and ecosystems

chemical diversity
: the variety of metabolic compounds in an ecosystem

ecosystem diversity
: the variety of ecosystems

endemic species
: a species native to one place

extinction
: the disappearance of a species from Earth; local extinction is the disappearance of a species from a region

genetic diversity
: the variety of genes and alleles in a species or other taxonomic group or ecosystem; the term can refer to allelic diversity or genome-wide diversity

habitat heterogeneity
: the number of ecological niches

secondary plant compound
: a compound produced as a byproduct of plant metabolic processes that is typically toxic, but is sequestered by the plant to defend against herbivores

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5.3: 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 below). 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.

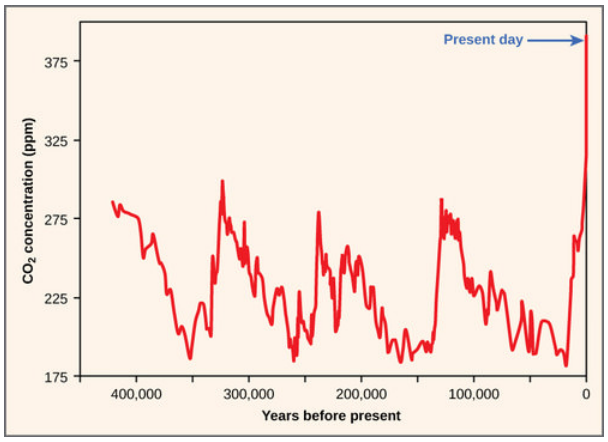


Figure 5.3.1: Atmospheric carbon dioxide levels fluctuate in a cyclical manner. However, the burning of fossil fuels in recent history has caused a dramatic increase in the levels of carbon dioxide in the Earth's atmosphere, which have now reached levels never before seen on Earth. Scientists predict that the addition of this "greenhouse gas" to the atmosphere is resulting in climate change that will significantly impact biodiversity in the coming century.

Habitat Loss

Humans rely on technology to modify their environment and 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 below). 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 5.3.2: 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

Explore a U.S. Fish & Wildlife Service interactive map of critical habitat for endangered and threatened species in the United States. To begin, select "Visit the 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.

Concept in Action

View a brief video discussing the role of marine ecosystems in supporting human welfare and the decline of ocean ecosystems.

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 below) 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.

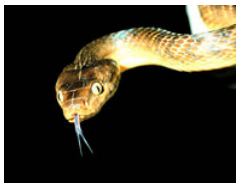


Figure 5.3.3: The brown tree snake, Boiga irregularis, is an exotic species that has caused numerous extinctions on the island of Guam since its accidental introduction in 1950. (credit: NPS)

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 below). 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.

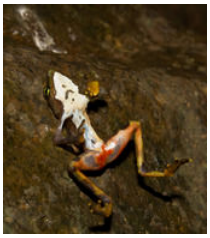


Figure 5.3.4: This Limosa harlequin frog (Atelopus limosus), an endangered species from Panama, died from a fungal disease called chytridiomycosis. The red lesions are symptomatic of the disease. (credit: Brian Gratwicke)

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 below). The disease has decimated bat populations and threatens extinction of species already listed as

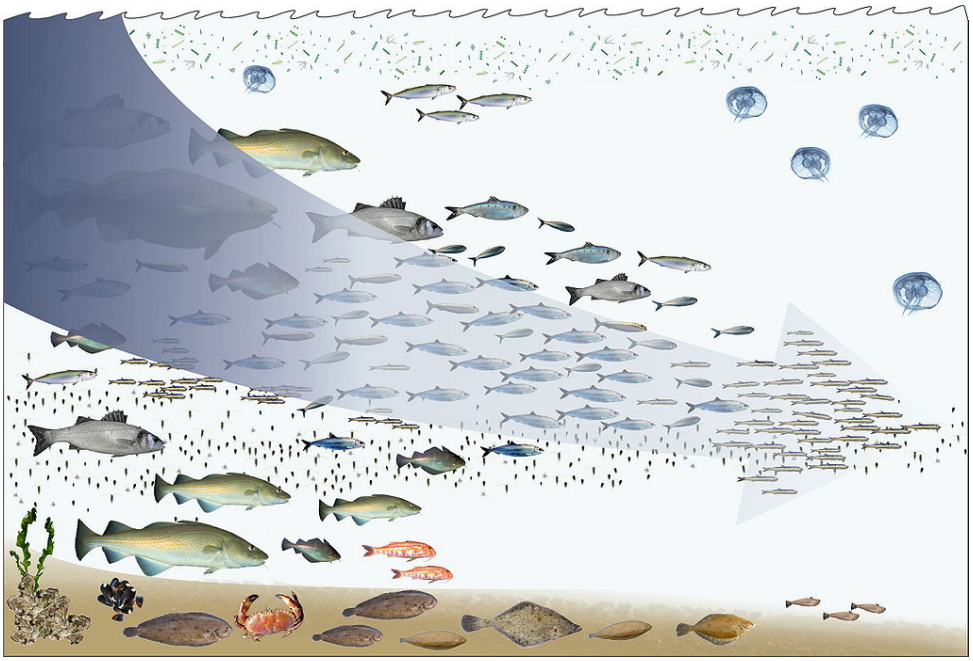
endangered: the Indiana bat, *Myotis sodalis*, and potentially the Virginia big-eared bat, *Corynorhinus townsendii virginianus*. How the fungus was introduced is unknown, but one logical presumption would be that recreational cavers unintentionally brought the fungus on clothes or equipment from Europe.



Figure 5.3.5: 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)

Disruption of Food Chains

Disruptions to food chains, also known as food web disruptions, occur when there are significant changes to the structure and function of an ecosystem's energy flow and species interactions. These disruptions can stem from various factors, including habitat loss, invasive species, pollution, and climate change, and can lead to imbalances within the ecosystem. As an example, "fishing down the food web" describes the process where fisheries, having depleted populations of large, predatory fish at the highest trophic levels within an ecosystem, shift their targeting efforts to increasingly smaller species at lower trophic levels. This practice results in a decline in the average trophic level of the fish caught in a particular area or globally



Fishing down the food chain. Attribution: © Hans Hillewaert. This file is licensed under the Creative Commons Attribution-Share Alike 4.0 International license.

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 below).



Figure 5.3.6: 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.

Other Threats

"HIPPO" is a common acronym that stands for threats to biodiversity. The acronym HIPPO is a mnemonic device used to remember the five major human-caused threats to biodiversity. It was coined by biologist E.O. Wilson. Each letter represents a different threat:

H - Habitat Loss: This refers to the destruction, degradation, and fragmentation of natural habitats that species rely on for survival. Examples include deforestation, clearing land for agriculture, development, and pollution of water sources.
I - Invasive Species: These are non-native species introduced into an ecosystem. They can outcompete native species, disrupt food webs, introduce diseases, and cause other negative impacts, potentially leading to the extinction of native species.
P - Pollution: This includes the discharge of harmful substances into the environment, such as toxic chemicals, heavy metals, pesticides, and excessive nutrients, which can negatively affect flora and fauna and lead to extinctions.
P - Population (Human): The increasing human population and resource consumption patterns put immense pressure on ecosystems and biodiversity. This drives habitat loss, increases pollution, and leads to overexploitation of resources.

O - Overharvesting (Overexploitation): This involves the unsustainable hunting, fishing, gathering, or collection of species, leading to their depletion or even extinction.

These five factors are interconnected and often exacerbated by climate change. Sometimes the acronym is expanded to HIPPCO, with the extra "C" standing for Climate Change, to highlight its significant role in driving biodiversity loss.

Contributors and Attributions

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5.4: Alpha, Beta, and Gamma Diversity

Whittaker (1972) described three terms for measuring biodiversity over spatial scales: alpha, beta, and gamma diversity. Alpha diversity refers to the diversity within a particular area or ecosystem, and is usually expressed by the number of species (i.e., **species richness**) in that ecosystem. For example, if we are monitoring the effect that British farming practices have on the diversity of native birds in a particular region of the country, then we might want to compare species diversity within different ecosystems, such as an undisturbed deciduous wood, a well-established hedgerow bordering a small pasture, and a large arable field. We can walk a transect in each of these three ecosystems and count the number of species we see; this gives us the alpha diversity for each ecosystem; see Table (this example is based on the hypothetical example given by Meffe et al., 2002; Table 6.1).

If we examine the change in species diversity between these ecosystems then we are measuring the beta diversity. We are counting the total number of species that are unique to each of the ecosystems being compared. For example, the beta diversity between the woodland and the hedgerow habitats is 7 (representing the 5 species found in the woodland but not the hedgerow, plus the 2 species found in the hedgerow but not the woodland). Thus, beta diversity allows us to compare diversity between ecosystems.

Gamma diversity is a measure of the overall diversity for the different ecosystems within a region. *Hunter (2002: 448)* defines gamma diversity as "geographic-scale species diversity". In the example in Table, the total number of species for the three ecosystems 14, which represent the gamma diversity.

Hypothetical species	Woodland habitat	Hedgerow habitat	Open field habitat
A	X		
B	X		
C	X		
D	X		
E	X		
F	X	X	
G	X	X	
H	X	X	
I	X	X	
J	X	X	
K		X	
L		X	X
M			X
N			X
Alpha diversity	10	7	3
Beta diversity	Woodland vs. hedgerow: 7	Hedgerow vs. open field: 8	Woodland vs. open field: 13
Gamma diversity	14		

Hypothetical species	Woodland habitat	Hedgerow habitat	Open field habitat
A	X		
B	X		
C	X		
D	X		
E	X		
F	X	X	
G	X	X	
H	X	X	
I	X	X	
J	X	X	
K		X	
L		X	X
M			X
N			X
Alpha diversity	10	7	3
Beta diversity	Woodland vs. hedgerow: 7	Hedgerow vs. open field: 8	Woodland vs. open field: 13
Gamma diversity	14		

Table 5.4.1 *Alpha, beta and gamma diversity for hypothetical species of birds in three different ecosystems*

Glossary

Ecosystem

a community plus the physical environment that it occupies at a given time

Alpha diversity

the diversity within a particular area or ecosystem; usually expressed by the number of species (i.e., species richness) in that ecosystem

Beta diversity

a comparison of of diversity between ecosystems, usually measured as the amount of species change between the ecosystems

Gamma diversity

a measure of the overall diversity within a large region. Geographic-scale species diversity according to Hunter (2002: 448)

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5.5: Population Diversity

A population is a group of individuals of the same species that share aspects of their genetics or demography more closely with each other than with other groups of individuals of that species (where demography is the statistical characteristic of the population such as size, density, birth and death rates, distribution, and movement of migration).

Population diversity may be measured in terms of the variation in genetic and morphological features that define the different populations. The diversity may also be measured in terms of the populations' demographics, such as numbers of individuals present, and the proportional representation of different age classes and sexes. However, it can be difficult to measure demography and genetics (e.g., allele frequencies) for all species. Therefore, a more practical way of defining a population, and measuring its diversity, is by the space it occupies. Accordingly, a population is a group of individuals of the same species occupying a defined area at the same time (Hunter, 2002: 144). The area occupied by a population is most effectively defined by the ecological boundaries that are important to the population (for example, a particular region and type of vegetation for a population of beetles, or a particular pond for a population of fish).

The geographic range and distribution of populations (i.e., their spatial structure) represent key factors in analyzing population diversity because they give an indication of likelihood of movement of organisms between populations and subsequent genetic and demographic interchange. Similarly, an estimate of the overall population size provides a measure of the potential genetic diversity within the population; large populations usually represent larger gene pools and hence greater potential diversity.

Isolated populations, with very low levels of interchange, show high levels of genetic divergence (Hunter, 2002: 145), and exhibit unique adaptations to the biotic and abiotic characteristics of their habitat. The genetic diversity of some groups that generally do not disperse well - such as amphibians, mollusks, and some herbaceous plants - may be mostly restricted to local populations (Avise, 1994). For this reason, range retractions of species can lead to loss of local populations and the genetic diversity they hold. Loss of isolated populations along with their unique component of genetic variation is considered by some scientists to be one of the greatest but most overlooked tragedies of the biodiversity crisis (Ehrlich & Raven 1969).

Populations can be categorized according to the level of divergence between them. Isolated and genetically distinct populations of a single species may be referred to as subspecies according to some (but not all) species concepts. Populations that show less genetic divergence might be recognized as variants or races. However, the distinctions between subspecies and other categories can be somewhat arbitrary (see Species diversity).

A species that is ecologically linked to a specialized, patchy habitat may likely assume the patchy distribution of the habitat itself, with several different populations distributed at different distances from each other. This is the case, for example, for species that live in wetlands, alpine zones on mountaintops, particular soil types or forest types, springs, and many other comparable situations. Individual organisms may periodically disperse from one population to another, facilitating genetic exchange between the populations. This group of different but interlinked populations, with each different population located in its own, discrete patch of habitat, is called a metapopulation.

There may be quite different levels of dispersal between the constituent populations of a metapopulation. For example, a large or overcrowded population patch is unlikely to be able to support much immigration from neighboring populations; it can, however, act as a source of dispersing individuals that will move away to join other populations or create new ones. In contrast, a small population is unlikely to have a high degree of emigration; instead, it can receive a high degree of immigration. A population that requires net immigration in order to sustain itself acts as a sink. The extent of genetic exchange between source and sink populations depends, therefore, on the size of the populations, the carrying capacity of the habitats where the populations are found, and the ability of individuals to move between habitats. Consequently, understanding how the patches and their constituent populations are arranged within the metapopulation, and the ease with which individuals are able to move among them is key to describing the population diversity and conserving the species. For more discussion, see the module on Metapopulations.

Glossary

Population

a group of individuals of the same species that share aspects of their demography or genetics more closely with each other than with other groups of individuals of that species

A population may also be defined as a group of individuals of the same species occupying a defined area at the same time (Hunter, 2002: 144)

Metapopulation

a group of different but interlinked populations, with each different population located in its own, discrete patch of habitat

Source

a population patch, in a metapopulation, from which individuals disperse to other population patches or create new ones

Sink

a population patch, in a metpopulation that does not have a high degree of emigration outside its boundaries but, instead, requires net immigration in order to sustain itself

Demography

the statistical characteristics of the population such as size, density, birth and death rates, distribution, and movement or migration.

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5.6: 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.

Change in Biodiversity through Time

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

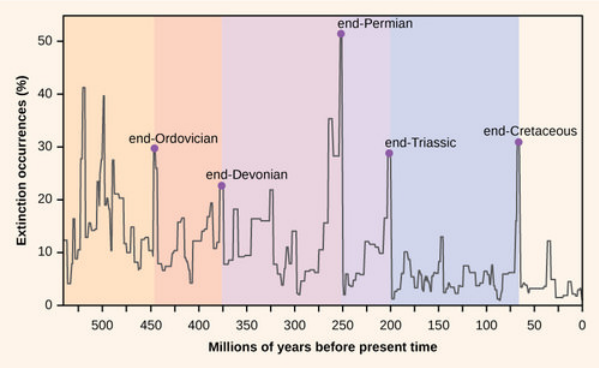


Figure 5.6.1: Extinction intensity as reflected in the fossil record has fluctuated throughout Earth’s history. Sudden and dramatic losses of biodiversity, called mass extinctions, have occurred five times.

Paleontologists have identified five 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 into their causes. An argument can be made that the five mass extinctions are only the five most extreme events in a continuous series of large extinction events throughout the fossil record (since 542 million years ago). In most cases, the hypothesized causes are still controversial; in one, the most recent, the cause seems clear. The most recent extinction in geological time, about 65 million years ago, saw the disappearance of the dinosaurs and many other species. Most scientists now agree the cause of this extinction was the impact of a large asteroid in the present-day Yucatán Peninsula and the subsequent energy release and global climate changes caused by dust ejected into the atmosphere.

Recent and Current Extinction Rates

A sixth, or Holocene, mass extinction has mostly to do with the activities of *Homo sapiens*. There are numerous recent extinctions of individual species that are recorded in human writings. Most of these are coincident with the expansion of the European colonies since the 1500s.

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

 Figure 5.6.2: The dodo bird was hunted to extinction around 1662. (credit: Ed Uthman, taken in Natural History Museum, London, England)

Steller's sea cow became extinct in 1768; it was related to the manatee and probably once lived along the northwest coast of North America. Steller's sea cow was discovered by Europeans in 1741, and it was hunted for meat and oil. A total of 27 years elapsed between the sea cow's first contact with Europeans and extinction of the species. The last Steller's sea cow was killed in 1768. In another example, the last living passenger pigeon died in a zoo in Cincinnati, Ohio, in 1914. This species had once migrated in the millions but declined in numbers because of overhunting and loss of habitat through the clearing of forests for farmland.

These are only a few of the recorded extinctions in the past 500 years. The International Union for Conservation of Nature (IUCN) keeps a list of extinct and endangered species called the Red List. The list is not complete, but it describes 380 vertebrates that became extinct after 1500 AD, 86 of which were driven extinct by overhunting or overfishing.

Estimates of Present-day Extinction Rates

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

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

A second approach to estimating present-time extinction rates is to correlate species loss with habitat loss, and it is based on measuring forest-area loss and understanding species–area relationships. The **species-area relationship** is the rate at which new species are seen when the area surveyed is increased (Figure below). Likewise, if the habitat area is reduced, the number of species seen will also decline. This kind of relationship is also seen in the relationship between an island's area and the number of species present on the island: as one increases, so does the other, though not in a straight line. Estimates of extinction rates based on habitat loss and species–area relationships have suggested that with about 90 percent of habitat loss an expected 50 percent of species would become extinct. Figure below shows that reducing forest area from 100 km^2 to 10 km^2, a decline of 90 percent, reduces the number of species by about 50 percent. Species–area estimates have led to estimates of present-day species extinction rates of about 1000 E/MSY and higher. In general, actual observations do not show this amount of loss and one explanation put forward is that there is a delay in extinction. According to this explanation, it takes some time for species to fully suffer the effects of habitat loss and they linger on for some time after their habitat is destroyed, but eventually they will become extinct. 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. Using an alternate method would bring estimates down to around 500 E/MSY in the coming century. Note that this value is still 500 times the background rate.

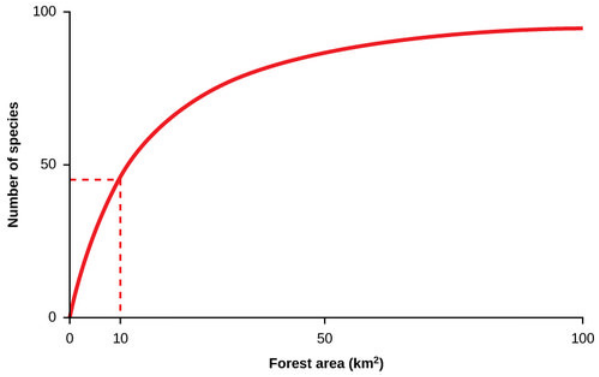


Figure 5.6.3: A typical species-area curve shows the cumulative number of species found as more and more area is sampled. The curve has also been interpreted to show the effect on species numbers of destroying habitat; a reduction in habitat of 90 percent from 100 km2 to 10 km2 reduces the number of species supported by about 50 percent.

Conservation of Biodiversity

The threats to biodiversity at the genetic, species, and ecosystem levels have been recognized for some time. In the United States, the first national park with land set aside to remain in a wilderness state was Yellowstone Park in 1890. However, attempts to preserve nature for various reasons have occurred for centuries. Today, the main efforts to preserve biodiversity involve legislative approaches to regulate human and corporate behavior, setting aside protected areas, and habitat restoration.

Changing Human Behavior

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

Within many countries there are laws that protect endangered species and that regulate hunting and fishing. In the United States, the Endangered Species Act was enacted in 1973. When an at-risk species is listed by the Act, the U.S. Fish & Wildlife Service is required by law to develop a management plan to protect the species and bring it back to sustainable numbers. The 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 a species 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 (although the management plans commonly involve protection of the individual species’ habitat) 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.

The Migratory Bird Treaty Act (MBTA) is an agreement between the United States and Canada that was signed into law in 1918 in response to declines in North American bird species caused by hunting. The Act now lists over 800 protected species. It makes it illegal to disturb or kill the protected species or distribute their parts (much of the hunting of birds in the past was for their feathers). Examples of protected species include northern cardinals, the red-tailed hawk, and the American black vulture.

Global warming is expected to be a major driver of biodiversity loss. Many governments are concerned about the effects of anthropogenic global warming, primarily on their economies and food resources. Since greenhouse gas emissions do not respect national boundaries, the effort to curb them is an international one. The international response to global warming has been mixed. The Kyoto Protocol, an international agreement that came out of the United Nations Framework Convention on Climate Change that committed countries to reducing greenhouse gas emissions by 2012, was ratified by some countries, but spurned by others. Two countries that were especially important in terms of their potential impact that did not ratify the Kyoto protocol were the United States and China. Some goals for reduction in greenhouse gasses were met and exceeded by individual countries, but, worldwide, the effort to limit greenhouse gas production is not succeeding. The intended replacement for the Kyoto Protocol has

not materialized because governments cannot agree on timelines and benchmarks. Meanwhile, the resulting costs to human societies and biodiversity predicted by a majority of climate scientists will be high.

As already mentioned, the non-profit, non-governmental sector plays a large role in conservation effort both in North America and around the world. The approaches range from species-specific organizations to the broadly focused IUCN and Trade Records Analysis of Flora and Fauna in Commerce (TRAFFIC). The Nature Conservancy takes a novel approach. It purchases land and protects it in an attempt to set up preserves for ecosystems. Ultimately, human behavior will change when human values change. At present, the growing urbanization of the human population is a force that mitigates against valuing biodiversity, because many people no longer come in contact with natural environments and the species that inhabit them.

Conservation in Preserves

Establishment of wildlife and ecosystem preserves is one of the key tools in conservation efforts (Figure below). 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 for protecting both species and ecosystems, but they have some serious drawbacks.



Figure 5.6.4: National parks, such as Grand Teton National Park in Wyoming, help conserve biodiversity. (credit: Don DeBold)

A simple measure of success in setting aside preserves for biodiversity protection is to set a target percentage of land or marine habitat to protect. However, a more detailed preserve design and choice of location is usually necessary because of the way protected lands are allocated and how biodiversity is distributed: protected lands tend to contain less economically valuable resources rather than being set aside specifically for the species or ecosystems at risk. In 2003, the IUCN World Parks Congress estimated that 11.5 percent of Earth's land surface was covered by preserves of various kinds. This area is greater than previous goals; however, it only represents 9 out of 14 recognized major biomes and research has shown that 12 percent of all species live outside preserves; these percentages are much higher when threatened species are considered and when only high quality preserves are considered. For example, high quality preserves include only about 50 percent of threatened amphibian species. The conclusion must be that either the percentage of area protected must be increased, the percentage of high quality preserves must be increased, or preserves must be targeted with greater attention to biodiversity protection. Researchers argue that more attention to the latter solution is required.

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

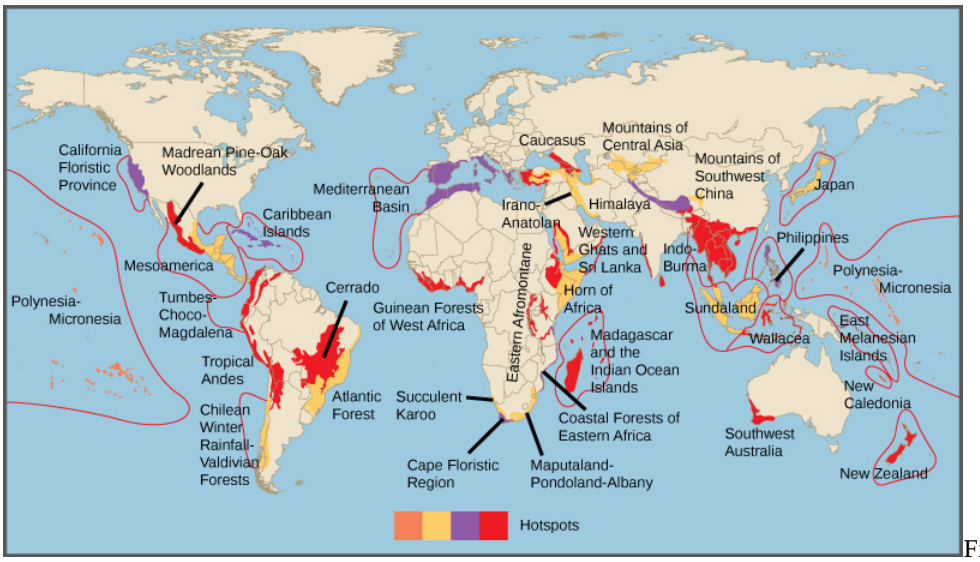


Figure 5.6.5: Conservation International has identified 34 biodiversity hotspots. Although these cover only 2.3 percent of the Earth's surface, 42 percent of the terrestrial vertebrate species and 50 percent of the world's plants are endemic to those hotspots.

There has been extensive research into optimal preserve designs for maintaining biodiversity. The fundamental principles behind much of the research have come from the seminal theoretical work of Robert H. MacArthur and Edward O. Wilson published in 1967 on island biogeography. This work sought to understand the factors affecting biodiversity on islands. Conservation preserves can be seen as "islands" of habitat within "an ocean" of non-habitat. In general, large preserves are better because they support more species, including species with large home ranges; they have more core area of optimal habitat for individual species; they have more niches to support more species; and they attract more species because they can be found and reached more easily.

Preserves perform better when there are partially protected buffer zones around them of suboptimal habitat. The buffer allows organisms to exit the boundaries of the preserve without immediate negative consequences from hunting 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 less hospitable ecosystems outside the preserve boundary. For this same reason, preserves in the shape of a square or circle will be better than a preserve with many thin "arms." If preserves must be smaller, then providing wildlife corridors between them so that species and their genes can move between the preserves; for example, preserves 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 specifications of a preserve, there are a variety of regulations related to the use of a preserve. These can include anything from timber extraction, mineral extraction, regulated hunting, human habitation, and nondestructive human recreation. Many of the decisions to include these other uses are made based on political pressures rather than conservation considerations. On the other hand, in some cases, wildlife protection policies have been so strict that subsistence-living indigenous populations have been forced from ancestral lands that fell within a preserve. In other cases, even if a preserve is designed to protect wildlife, if the protections are not or cannot be enforced, the preserve status will have little meaning in the face of illegal poaching and timber extraction. This is a widespread problem with preserves in the tropics.

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, never larger, so setting aside areas that are large enough is difficult. 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 as the species within them migrate to higher latitudes as the habitat of the preserve becomes less favorable. Planning for the effects of global warming on future preserves, or adding new preserves to accommodate the changes expected from global warming is in progress, but will only be as effective as the accuracy of the predictions of the effects of global warming on future habitats.

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

Habitat Restoration

Habitat restoration holds considerable promise as a mechanism for maintaining or restoring biodiversity. Of course once a species has become extinct, its restoration is impossible. However, restoration can improve the biodiversity of degraded ecosystems. Reintroducing wolves, a top predator, to Yellowstone National Park in 1995 led to dramatic changes in the ecosystem that increased biodiversity. The wolves (Figure below) function to suppress elk and coyote populations and provide more abundant resources to the guild of carrion eaters. Reducing elk populations has allowed revegetation of riparian (the areas along the banks of a stream or river) areas, which has increased the diversity of species in that habitat. Suppression of coyotes has increased the species previously suppressed by this predator. The number of species of carrion eaters has increased because of the predatory activities of the wolves. In this habitat, the wolf is a keystone species, meaning a species that is instrumental in maintaining diversity within an ecosystem. Removing a keystone species from an ecological community causes a collapse in diversity. The results from the Yellowstone experiment suggest that restoring a keystone species effectively can have the effect of restoring biodiversity in the community. Ecologists have argued for the identification of keystone species where possible and for focusing protection efforts on these species. It makes sense to return the keystone species to the ecosystems where they have been removed.



Figure 5.6.6: This photograph shows the Gibbon wolf pack in Yellowstone National Park, March 1, 2007. Wolves have been identified as a keystone species. (credit: Doug Smith, NPS)

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

The Role of Zoos and Captive Breeding

Zoos have sought to play a role in conservation efforts both through captive breeding programs and education (Figure below). The transformation of the missions of zoos from collection and exhibition facilities to organizations that are dedicated to conservation is ongoing. In general, it has been recognized that, except in some specific targeted cases, captive breeding programs for endangered species are inefficient and often prone to failure when the species are reintroduced to the wild. Zoo facilities are far too limited to contemplate captive breeding programs for the numbers of species that are now at risk. Education, on the other hand, is a potential positive impact of zoos on conservation efforts, particularly given the global trend to urbanization and the consequent reduction in

contacts between people and wildlife. A number of studies have been performed to look at the effectiveness of zoos on people's attitudes and actions regarding conservation; at present, the results tend to be mixed.



Figure 5.6.7: Zoos and captive breeding programs help preserve many endangered species, such as this golden lion tamarin. (credit: Garrett Ziegler)

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5.7: Biodiversity Change through Geological Time

Learning Objectives

- Describe how biodiversity has changed through geological time as a result of mass extinctions

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 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.

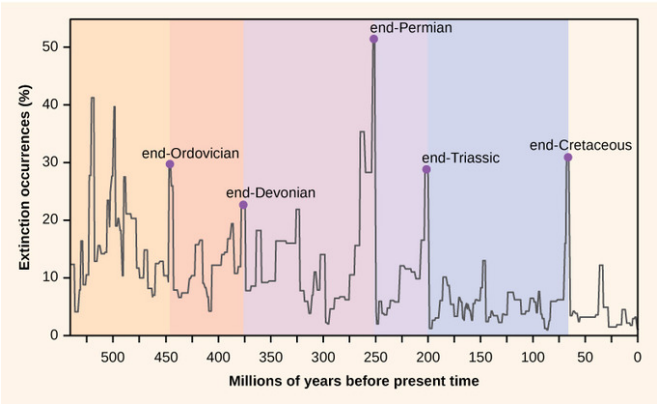


Figure 5.7.1: Fossil record: Extinction occurrences, as reflected in the fossil record, have fluctuated throughout earth's history. Sudden and dramatic losses of biodiversity, called mass extinctions, have occurred five times.

Paleontologists have identified five strata in the fossil record that appear to show sudden and dramatic losses in biodiversity known as 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.

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.

Mass Extinctions		
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

Figure 5.7.1: Five mass extinctions: The transitions between the five main mass extinctions can be seen in the rock strata. The table shows the time that elapsed between each period.

The Ordovician-Silurian extinction event is the first-recorded mass extinction and the second largest. During this period, about 85 percent of marine species (few species lived outside the oceans) became extinct. The main hypothesis for its cause was a period of glaciation followed by warming. These two extinction events, cooling and warming, were separated by about 1 million years; the

climate changes affected temperatures and sea levels. Some researchers have suggested that a gamma-ray burst caused by a nearby supernova is a possible cause of the Ordovician-Silurian extinction. The gamma-ray burst would have stripped away the earth's ozone layer, causing intense ultraviolet radiation from the sun. It may account for climate changes observed at the time.

The late Devonian extinction may have occurred over a relatively long period of time. Its causes are poorly-understood and it appears to have have affected only marine species.

The end-Permian extinction was the largest in the history of life. Estimates predict that 96 percent of all marine species and 70 percent of all terrestrial species were lost.The causes for this mass extinction are not clear, but the leading suspect is extended and widespread volcanic activity that led to a runaway global-warming event. The oceans became largely anoxic, suffocating marine life. Terrestrial tetrapod diversity took 30 million years to recover after the end-Permian extinction. The Permian extinction dramatically altered earth's biodiversity composition and the course of evolution.

The causes of the Triassic–Jurassic extinction event are not clear. Hypotheses of climate change, asteroid impact, and volcanic eruptions have been argued. The extinction event occurred just before the breakup of the supercontinent Pangaea; although, recent scholarship suggests that the extinctions may have occurred more gradually throughout the Triassic.

The causes of the end-Cretaceous extinction event are the ones that are best understood. It was during this extinction event, about 65 million years ago, that the dinosaurs, the dominant vertebrate group for millions of years, disappeared from the planet (with the exception of a theropod clade that gave rise to birds). Indeed, every land animal that weighed more then 25 kg became extinct. The cause of this extinction is now understood to be the result of a cataclysmic impact of a large meteorite or asteroid off the coast of what is now the Yucatán Peninsula. This hypothesis, proposed first in 1980, was a radical explanation based on a sharp spike in the levels of iridium (which rains down from space in meteors at a fairly constant rate, but is otherwise absent on earth's surface) at the rock stratum that marks the boundary between the Cretaceous and Paleogene periods. The Cretaceous-Paleogene (K-Pg) boundary marked the disappearance of the dinosaurs in fossils, as well as many other taxa. The researchers who discovered the iridium spike interpreted it as a rapid influx of iridium from space to the atmosphere (in the form of a large asteroid), rather than a slowing in the deposition of sediments during that period. It was a radical explanation, but the report of an appropriately aged and sized impact crater in 1991 made the hypothesis more credible. Now, an abundance of geological evidence supports the hypothesis. Recovery times for biodiversity after the end-Cretaceous extinction were shorter, in geological time, than for the end-Permian extinction: on the order of 10 million years.



Figure 5.7.1: K-Pg mass extinction: In 1980, Luis and Walter Alvarez, Frank Asaro, and Helen Michels discovered, across the world, a spike in the concentration of iridium within the sedimentary layer at the K–Pg boundary. These researchers hypothesized that this iridium spike was caused by an asteroid impact that resulted in the K–Pg mass extinction. In the photo, the iridium layer is the light band.

Key Points

- Fossil records have been instrumental in differentiating between five periods that appear to show sudden and dramatic losses in biodiversity.
- Although there have been smaller periods of extinction, the five mass extinction periods demonstrate a continuous series of large extinction events.

- The Ordovician-Silurian extinction event was caused by glaciation followed by warming; it led to the extinction of 85 percent of marine species.
- The late Devonian extinction affected only marine species; the end- Permian extinction, the largest in history, may have been caused by volcanic activity, leading to a global-warming type event.
- The Triassic–Jurassic extinction event may have been caused by climate change, asteroid impact, or volcanic eruptions; however, the main cause is still unclear.
- The end- Cretaceous extinction event, in which the extinction of the dinosaurs occurred, is believed to have been caused by the impact of a large asteroid.

Key Terms

- **macroevolution**: large-scale patterns or processes in the history of life, including the origins of novel organism designs, evolutionary trends, adaptive radiations and extinctions
- **theropod**: any large, bipedal dinosaur, of the suborder Theropoda, from the Jurassic and Cretaceous periods
- **anoxic**: suffering from a reduced supply of oxygen

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5.8: Community Diversity

A community comprises the populations of different species that naturally occur and interact in a particular environment. Some communities are relatively small in scale and may have well-defined boundaries. Some examples are: species found in or around a desert spring, the collection of species associated with ripening figs in a tropical forest, those clustered around a hydrothermal vent on the ocean floor, those in the spray zone of a waterfall, or under warm stones in the alpine zone on a mountaintop. Other communities are larger, more complex, and may be less clearly defined, such as old-growth forests of the northwest coast of North America, lowland fen communities of the British Isles, or the community of freshwater species of Lake Baikal.

Sometimes biologists apply the term "community" to a subset of organisms within a larger community. For example, some biologists may refer to the "community" of species specialized for living and feeding entirely in the forest canopy, whereas other biologists may refer to this as part of a larger forest community. This larger forest community includes those species living in the canopy, those on the forest floor, and those moving between these two habitats, as well as the functional interrelationships between all of these. Similarly, some biologists working on ecosystem management might distinguish between the community of species that are endemic to an area (e.g. species that are endemic to an island) as well as those "exotic" species that have been introduced to that area. The introduced species form part of the larger, modified community of the area, but might not be considered as part of the regions original and distinctive community.

Communities are frequently classified by their overall appearance, or **physiognomy**. For example, coral reef communities are classified according to the appearance of the reefs where they are located, i.e., fringing reef communities, barrier reef communities, and atoll communities. Similarly, different stream communities may be classified by the physical characteristics of that part of the stream where the community is located, such as riffle zone communities and pool communities. However, one of the easiest, and hence most frequent methods of community classification is based on the dominant types of species present for example, intertidal mussel bed communities, Ponderosa pine forest communities of the Pacific northwest region of the U.S., or Mediterranean scrubland communities. Multivariate statistics provide more complex methods for diagnosing communities, for example, by arranging species on coordinate axes (e.g., x-y axes) that represent gradients in environmental factors such as temperature or humidity. For more information, see the module on "Natural communities in space and time."

The factors that determine the diversity of a community are extremely complex. There are many theories on what these factors are and how they determine community and ecosystem diversity. Environmental factors, such as temperature, precipitation, sunlight, and the availability of inorganic and organic nutrients are very important in shaping communities and ecosystems. Hunter (2002: 81) notes that, generally speaking, organisms can persist and evolve in places where there are sufficient environmental resources for the organisms to channel energy into growth and reproduction rather than simply the metabolic requirements for survival. In other words, organisms are less likely to thrive in a harsh environment with low energy resources. One way of measuring community diversity is to examine the energy flow through food webs that unite the species within the community; the extent of community diversity can be measured by the number of links in the food web. However, in practice, it can be very difficult to quantify the functional interactions between the species within a community. It is easier to measure the genetic diversity of the populations in the community, and to count the numbers of species present, and use these measures of genetic diversity and species richness as proxies for describing the functional diversity of the community. The evolutionary or taxonomic diversity of the species present is another way of measuring the diversity of a community, for application to conservation biology.

Glossary

Ecosystem

a community plus the physical environment that it occupies at a given time.

Community

the populations of different species that naturally occur and interact in a particular environment

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5.9: Ecosystem Diversity

An ecosystem is a community plus the physical environment that it occupies at a given time. An ecosystem can exist at any scale, for example, from the size of a small tide pool up to the size of the entire biosphere. However, lakes, marshes, and forest stands represent more typical examples of the areas that are compared in discussions of ecosystem diversity.

Broadly speaking, the diversity of an ecosystem is dependent on the physical characteristics of the environment, the diversity of species present, and the interactions that the species have with each other and with the environment. Therefore, the functional complexity of an ecosystem can be expected to increase with the number and taxonomic diversity of the species present, and the vertical and horizontal complexity of the physical environment. However, one should note that some ecosystems (such as submarine black smokers, or hot springs) that do not appear to be physically complex, and that are not especially rich in species, may be considered to be functionally complex. This is because they include species that have remarkable biochemical specializations for surviving in the harsh environment and obtaining their energy from inorganic chemical sources (e.g., see discussions of Rothschild and Mancinelli, 2001).

The physical characteristics of an environment that affect ecosystem diversity are themselves quite complex (as previously noted for community diversity). These characteristics include, for example, the temperature, precipitation, and topography of the ecosystem. Therefore, there is a general trend for warm tropical ecosystems to be richer in species than cold temperate ecosystems (see "Spatial gradients in biodiversity"). Also, the energy flux in the environment can significantly affect the ecosystem. An exposed coastline with high wave energy will have a considerably different type of ecosystem than a low-energy environment such as a sheltered salt marsh. Similarly, an exposed hilltop or mountainside is likely to have stunted vegetation and low species diversity compared to more prolific vegetation and high species diversity in sheltered valleys (see Walter, 1985, and Smith, 1990 for general discussions on factors affecting ecosystems, and comparative ecosystem ecology).

Environmental disturbance on a variety of temporal and spatial scales can affect the species richness and, consequently, the diversity of an ecosystem. For example, river systems in the North Island of New Zealand have been affected by volcanic disturbance several times over the last 25,000 years. Ash-laden floods running down the rivers would have extirpated most of the fish fauna in the rivers, and recolonization has been possible only by a limited number of diadromous species (i.e., species, like eels and salmons, that migrate between freshwater and seawater at fixed times during their life cycle). Once the disturbed rivers had recovered, the diadromous species would have been able to recolonize the rivers by dispersal through the sea from other unaffected rivers (McDowall, 1996).

Nevertheless, moderate levels of occasional disturbance can also increase the species richness of an ecosystem by creating spatial heterogeneity in the ecosystem, and also by preventing certain species from dominating the ecosystem. (See the module on Organizing Principles of the Natural World for further discussion).

Ecosystems may be classified according to the dominant type of environment, or dominant type of species present; for example, a salt marsh ecosystem, a rocky shore intertidal ecosystem, a mangrove swamp ecosystem. Because temperature is an important aspect in shaping ecosystem diversity, it is also used in ecosystem classification (e.g., cold winter deserts, versus warm deserts) (Udvardy, 1975).

While the physical characteristics of an area will significantly influence the diversity of the species within a community, the organisms can also modify the physical characteristics of the ecosystem. For example, stony corals (Scleractinia) are responsible for building the extensive calcareous structures that are the basis for coral reef ecosystems that can extend thousands of kilometers (e.g. Great Barrier Reef). There are less extensive ways in which organisms can modify their ecosystems. For example, trees can modify the microclimate and the structure and chemical composition of the soil around them. For discussion of the geomorphic influences of various invertebrates and vertebrates see (Butler, 1995) and, for further discussion of ecosystem diversity see the module on Processes and functions of ecological systems .

Glossary

Ecosystem

a community plus the physical environment that it occupies at a given time

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5.10: Present-Time Extinctions

Learning Objectives

- Describe the biodiversity loss during the Holocene extinction

Present-Time Extinctions

The sixth, or Holocene, mass extinction appears to have begun earlier than previously believed and is mostly due to the activities of *Homo sapiens*. Since the beginning of the Holocene period, there have been numerous recent extinctions of individual species that are recorded in human writings. Most of these coincide with the expansion of the European colonies in the 1500s.

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

Another example, Steller's sea cows, became extinct in 1768.The sea cow, first discovered by Europeans in 1741, was hunted for meat and oil. The last of the species was killed in 1768, which amounts to 27 years between the species' first contact with Europeans and its extinction. In addition, the last living passenger pigeon died in a zoo in Cincinnati, Ohio in 1914. This species was hunted and suffered from habitat loss through the clearing of forests for farmland. Furthermore, in 1918, the last living Carolina parakeet died in captivity. This species, once common in the eastern United States, was a victim of habitat loss and hunting as well. Adding to the extinction list, the Japanese sea lion, which inhabited a broad area around Japan and the coast of Korea, became extinct in the 1950s due to overfishing. The Caribbean monk seal, found in the Caribbean Sea, was driven to extinction through 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 made extinct by over-hunting 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 since there are many organisms that are of less interest to humans 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.

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 underestimated 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. Secondly, the number of recently-extinct species is increasing because extinct species now are being described from skeletal remains. Lastly, 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-day 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. Studies 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 habitats as well. 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, suggesting 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. Note that this value is still 500 times the background rate.

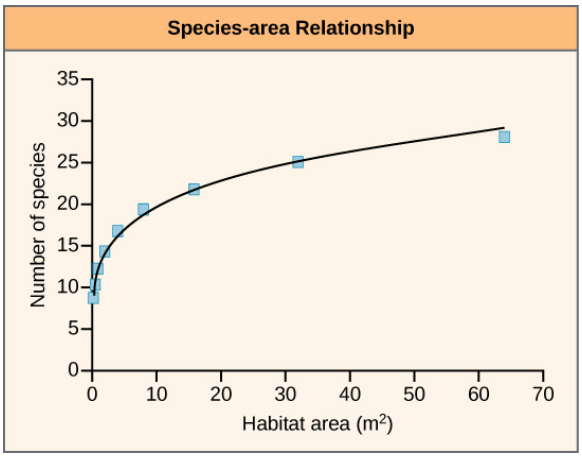


Figure 5.10.1: Species-area extinction estimates: Studies have shown that the number of species that are present increases with the size of the habitat. As habitat is lost, the number of species present will decrease.

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Key Points

- The dodo was one of the first-known examples of a species that went extinct (in the 1600s) during the Holocene period.
- Steller's sea cows, passenger pigeons, Carolina parakeets, Japanese sea lions, and Caribbean monk seals are examples of species that went extinct from the 1700s-1900s.
- Major reasons for species extinctions during the Holocene period are due to overhunting, overfishing, and other human-related activities.
- Extinction rates can be estimated by comparing extinction events since the 1500s, but this method may underestimate the actual extinction rate value.
- Extinction rates can be estimated by observing species-area relationships and correlating species loss with habitat loss; however, this method may lead to overestimation.

Key Terms

- **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
- **Holocene**: of a geologic epoch within the Neogene period from about 11,000 years ago to the present
- **extinction rate**: number of species becoming extinct over time, sometimes defined as extinctions per million species–years to make numbers manageable (E/MSY)

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CHAPTER OVERVIEW

6: Biomes

6.1: What constitutes a biome?

6.2: Terrestrial Biomes

6.3: Aquatic and Marine Biomes

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6.1: What constitutes a biome?

Learning Objectives

- Differentiate biomes from other levels of ecological classification, including habitat

What Constitutes a Biome?

A group of living organisms of the same kind that live in the same place simultaneously is known as a population. Populations live together in habitats, which together make up a community. An ecosystem is a community of living organisms interacting with the non-living components of that environment.

A biome is a community on a global scale, where habitats flank each other, and is usually defined by the temperature, precipitation, and types of plants and animals that inhabit it. The Earth's biomes are categorized into two major groups: terrestrial and aquatic. Terrestrial biomes are based on land, while aquatic biomes include both ocean and freshwater biomes. The major types of biomes include: aquatic, desert, forest, grassland, savannas, and tundra.

Biome Attributes

Generally, biome classification is determined by the climate and geography of an area. Each biome consists of communities that have adapted to the different climate and environment inside the biome. Specifically, there are special vegetation adaptations as well as physical and behavioral adaptions made by animals in order to accommodate the environment. 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.

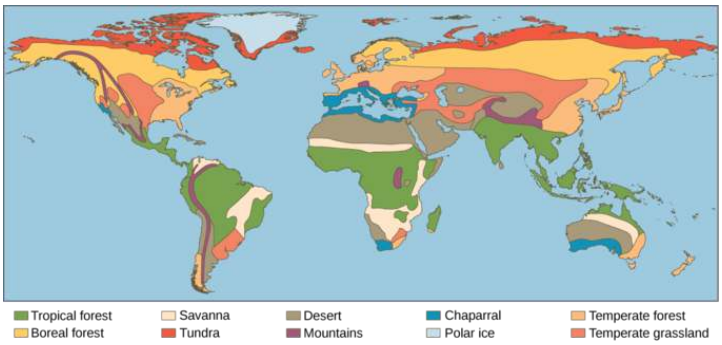


Figure 6.1.1: Earth's Major Biomes: Each of the world's major biomes is distinguished by characteristic temperatures and amounts of precipitation. Each type of biome can be found in multiple places.

The distribution of these biomes shows that the same biome can occur in geographically distinct areas with similar climates. Biomes have no distinct boundaries. Instead, there is a transition zone called an ecotone, which contains a variety of plants and animals. For example, an ecotone might be a transition region between a grassland and a desert, with species from both.

Key Points

- The climate, including precipitation and temperature, and the geography control the type of biome found in a region.
- There are two major classifications of biomes, which are terrestial and aquatic, and these include the types of biomes known as deserts, forests, grasslands, savannas, tundra, and freshwater environments.
- A habitat is the location where a group of one type of organism (a population) lives, while a biome is a community made of all the habitats in a given region and climate.
- Different organisms inhabit different types of biomes.
- Each type of biome can be found in multiple locations on Earth depending on its climate, geography, and organisms.

Key Terms

- **biome**: any major regional biological community such as that of forest or desert
- **ecotone**: a transition area between two adjacent ecosystems
- **habitat**: a specific place or natural conditions in which a plant or animal lives
- **population**: a collection of organisms of a particular species, sharing a particular characteristic of interest, most often that of living in a given area
- **ecosystem**: a system formed by an ecological community and its environment that functions as a unit

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6.2: Terrestrial Biomes

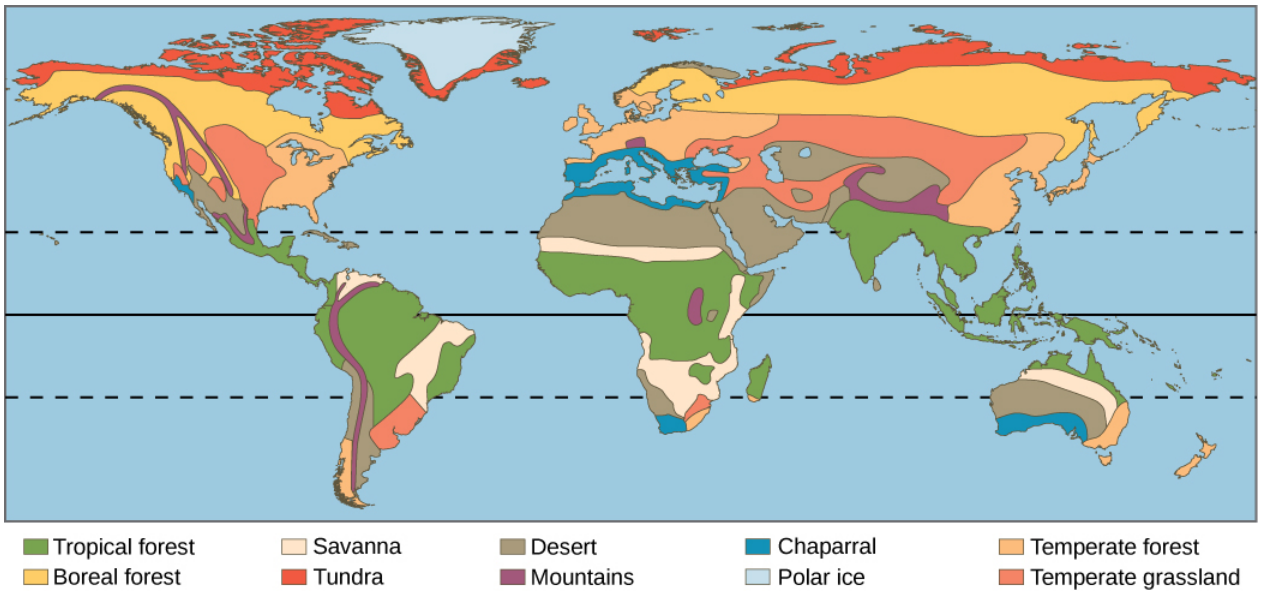


Figure 6.2.1***.*** *Each of the world's eight major biomes is distinguished by characteristic temperatures and amount of precipitation. Polar ice caps and mountains are also shown.*

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

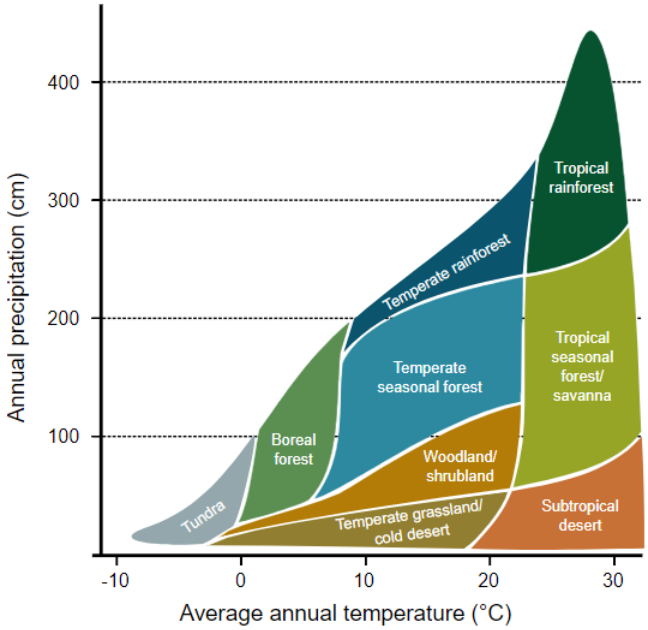


Figure 6.2.2. Precipitation and temperature are the two most important climatic variables that determine the type of biome in a particular location. Credit: "Climate influence on terrestrial biome" by Navarras is in the Public Domain, CC0

Tropical rainforests are found in equatorial regions (Figure 6.2.1) are the most biodiverse terrestrial biome. This biodiversity is under extraordinary threat primarily through logging and deforestation for agriculture. Tropical rainforests have also been described as nature's pharmacy because of the potential for new drugs that is largely hidden in the chemicals produced by the huge diversity

of plants, animals, and other organisms. The vegetation is characterized by plants with spreading roots and broad leaves that fall off throughout the year, unlike the trees of deciduous forests that lose their leaves in one season.

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

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



Figure 6.2.3. Species diversity is very high in tropical wet forests, such as these forests of Madre de Dios, Peru, near the Amazon River. (credit: Roosevelt Garcia)

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



Figure 6.2.4***.*** *A MinuteEarth video about how trees create rainfall, and vice versa.*



Figure 6.2.5. Although savannas are dominated by grasses, small woodlands, such as this one in Mount Archer National Park in Queensland, Australia, may dot the landscape. (credit: "Ethel Aardvark"/Wikimedia Commons)

Subtropical deserts exist between 15° and 30° north and south latitude and are centered on the Tropic of Cancer and the Tropic of Capricorn (Figure 6.2.6 below). Deserts are frequently located on the downwind or lee side of mountain ranges, which create a rain shadow after prevailing winds drop their water content on the mountains. This is typical of the North American deserts, such as the Mohave and Sonoran deserts. Deserts in other regions, such as the Sahara Desert in northern Africa or the Namib Desert in southwestern Africa are dry because of the high-pressure, dry air descending at those latitudes. Subtropical deserts are very dry; evaporation typically exceeds precipitation. Subtropical hot deserts can have daytime soil surface temperatures above 60°C (140°F) and nighttime temperatures approaching 0°C (32°F). Subtropical deserts are characterized by low annual precipitation of fewer than 30 cm (12 in) with little monthly variation and lack of predictability in rainfall. Some years may receive tiny amounts of rainfall, while others receive more. In some cases, the annual rainfall can be as low as 2 cm (0.8 in) in subtropical deserts located in central Australia ("the Outback") and northern Africa.



Figure 6.2.6***.*** *A MinuteEarth video about the global climate patterns which lead to subtropical deserts.*

The low species diversity of this biome is closely related to its low and unpredictable precipitation. Despite the relatively low diversity, desert species exhibit fascinating adaptations to the harshness of their environment. Very dry deserts lack perennial vegetation that lives from one year to the next; instead, many plants are annuals that grow quickly and reproduce when rainfall does occur, then they die. Perennial plants in deserts are characterized by adaptations that conserve water: deep roots, reduced foliage, and water-storing stems (Figure 6.2.6 below). Seed plants in the desert produce seeds that can lie dormant for extended periods between rains. Most animal life in subtropical deserts has adapted to a nocturnal life, spending the hot daytime hours beneath the ground. The Namib Desert is the oldest on the planet, and has probably been dry for more than 55 million years. It supports a number of endemic species (species found only there) because of this great age. For example, the unusual gymnosperm *Welwitschia mirabilis*is the only extant species of an entire order of plants. There are also five species of reptiles considered endemic to the Namib.

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



Figure 6.2.7. Many desert plants have tiny leaves or no leaves at all to reduce water loss. The leaves of ocotillo, shown here in the Chihuahuan Desert in Big Bend National Park, Texas, appear only after rainfall and then are shed. (credit “bare ocotillo”: “Leaflet”/Wikimedia Commons)

The **chaparral** is also called scrub forest and is found in California, along the Mediterranean Sea, and along the southern coast of Australia (Figure 6.2.7 below). The annual rainfall in this biome ranges from 65 cm to 75 cm (25.6–29.5 in) and the majority of the rain falls in the winter. Summers are very dry and many chaparral plants are dormant during the summertime. The chaparral vegetation is dominated by shrubs and is adapted to periodic fires, with some plants producing seeds that germinate only after a hot fire. The ashes left behind after a fire are rich in nutrients like nitrogen and fertilize the soil, promoting plant regrowth. Fire is a natural part of the maintenance of this biome.



Figure 6.2.8. The chaparral is dominated by shrubs. (credit: Miguel Vieira)

Temperate grasslands are found throughout central North America, where they are also known as prairies, and in Eurasia, where they are known as steppes (Figure 6.2.8 below). Temperate grasslands have pronounced annual fluctuations in temperature with hot summers and cold winters. The annual temperature variation produces specific growing seasons for plants. Plant growth is possible when temperatures are warm enough to sustain plant growth, which occurs in the spring, summer, and fall.

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



Figure 6.2.9. 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 ARS)*

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

Temperate forests are the most common biome in eastern North America, Western Europe, Eastern Asia, Chile, and New Zealand (Figure 6.2.9 below). This biome is found throughout mid-latitude regions. Temperatures range between –30°C and 30°C (–22°F to 86°F) and drop to below freezing on an annual basis. These temperatures mean that temperate forests have defined growing seasons during the spring, summer, and early fall. Precipitation is relatively constant throughout the year and ranges between 75 cm and 150 cm (29.5–59 in).

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

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



Figure 6.2.10. Deciduous trees are the dominant plant in the temperate forest. (credit: Oliver Herold)

The **boreal forest,** also known as **taiga** or **coniferous forest**, is found roughly between $50^{o}$and 60° north latitude across most of Canada, Alaska, Russia, and northern Europe (Figure 6.2.10 below). Boreal forests are also found above a certain elevation (and below high elevations where trees cannot grow) in mountain ranges throughout the Northern Hemisphere. This biome has cold, dry winters and short, cool, wet summers. The annual precipitation is from 40 cm to 100 cm (15.7–39 in) and usually takes the form of snow; relatively little evaporation occurs because of the cool temperatures.

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



Figure 6.2.11. The boreal forest (taiga) has low lying plants and conifer trees. (credit: L.B. Brubaker, NOAA)

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

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



Figure 6.2.12. Low-growing plants such lichen and grasses are common in tundra. Credit: *Nunavut tundra by Flickr: My Nunavut is licensed under CC BY 2.0*

Plants in the Arctic tundra are generally low to the ground and include low shrubs, grasses, lichens, and small flowering plants (Figure 6.2.11 below). There is little species diversity, low net primary productivity, and low above-ground biomass. The soils of the Arctic tundra may remain in a perennially frozen state referred to as permafrost. The permafrost makes it impossible for roots to penetrate far into the soil and slows the decay of organic matter, which inhibits the release of nutrients from organic matter. The melting of the permafrost in the brief summer provides water for a burst of productivity while temperatures and long days permit it. During the growing season, the ground of the Arctic tundra can be completely covered with plants or lichens.

Suggested Supplementary Reading

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

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6.3: Aquatic and Marine Biomes

Like terrestrial biomes, aquatic biomes are influenced by abiotic factors. In the case of aquatic biomes the abiotic factors include light, temperature, flow regime, and dissolved solids. The aquatic medium—water— has different physical and chemical properties than air. Even if the water in a pond or other body of water is perfectly clear (there are no suspended particles), water, on its own, absorbs light. As one descends deep enough into a body of water, eventually there will be a depth at which the sunlight cannot reach. While there are some abiotic and biotic factors in a terrestrial ecosystem that shade light (like fog, dust, or insect swarms), these are not usually permanent features of the environment. The importance of light in aquatic biomes is central to the communities of organisms found in both freshwater and marine ecosystems because it controls productivity through photosynthesis.

In addition to light, solar radiation warms bodies of water and many exhibit distinct layers of water at differing temperatures. The water temperature affects the organisms' rates of growth and the amount of dissolved oxygen available for respiration.

The movement of water is also important in many aquatic biomes. In rivers, the organisms must obviously be adapted to the constant movement of the water around them, but even in larger bodies of water such as the oceans, regular currents and tides impact availability of nutrients, food resources, and the presence of the water itself.

Finally, all natural water contains dissolved solids, or salts. Fresh water contains low levels of such dissolved substances because the water is rapidly recycled through evaporation and precipitation. The oceans have a relatively constant high salt content. Aquatic habitats at the interface of marine and freshwater ecosystems have complex and variable salt environments that range between freshwater and marine levels. These are known as brackish water environments. Lakes located in closed drainage basins concentrate salt in their waters and can have extremely high salt content that only a few and highly specialized species are able to inhabit.

Marine Biomes

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

The ocean is categorized by several zones (Figure 6.3.2). All of the ocean's open water is referred to as the pelagic realm (or zone). The benthic realm (or zone) extends along the ocean bottom from the shoreline to the deepest parts of the ocean floor. From the surface to the bottom or the limit to which photosynthesis occurs is the photic zone (approximately 200 m or 650 ft). At depths greater than 200 m, light cannot penetrate; thus, this is referred to as the aphotic zone. The majority of the ocean is aphotic and lacks sufficient light for photosynthesis. The deepest part of the ocean, the Challenger Deep (in the Mariana Trench, located in the western Pacific Ocean), is about 11,000 m (about 6.8 mi) deep. To give some perspective on the depth of this trench, the ocean is, on average, 4267 m or 14,000 ft deep.

Ocean

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

The intertidal zone (Figure 6.3.2) is the oceanic region that is closest to land. With each tidal cycle, the intertidal zone alternates between being inundated with water and left high and dry. Generally, most people think of this portion of the ocean as a sandy beach. In some cases, the intertidal zone is indeed a sandy beach, but it can also be rocky, muddy, or dense with tangled roots in mangrove forests. The intertidal zone is an extremely variable environment because of tides. Organisms may be exposed to air at low tide and are underwater during high tide. Therefore, living things that thrive in the intertidal zone are often adapted to being dry for long periods of time. The shore of the intertidal zone is also repeatedly struck by waves and the organisms found there are adapted to withstand damage from the pounding action of the waves (Figure 6.3.1). The exoskeletons of shoreline crustaceans (such as the shore crab, *Carcinus maenas*) are tough and protect them from desiccation (drying out) and wave damage. Another consequence of the pounding waves is that few algae and plants establish themselves in constantly moving sand or mud.



Figure 6.3.1**:** Sea stars, sea urchins, and mussel shells are often found in the intertidal zone, shown here in Kachemak Bay, Alaska. (credit: NOAA)

The neritic zone (Figure 6.3.2) extends from the margin of the intertidal zone to depths of about 200 m (or 650 ft) at the edge of the continental shelf. When the water is relatively clear, photosynthesis can occur in the neritic zone. The water contains silt and is well-oxygenated, low in pressure, and stable in temperature. These factors all contribute to the neritic zone having the highest productivity and biodiversity of the ocean. Phytoplankton, including photosynthetic bacteria and larger species of algae, are responsible for the bulk of this primary productivity. Zooplankton, protists, small fishes, and shrimp feed on the producers and are the primary food source for most of the world's fisheries. The majority of these fisheries exist within the neritic zone.

Beyond the neritic zone is the open ocean area known as the oceanic zone (Figure 6.3.2). Within the oceanic zone there is thermal stratification. Abundant phytoplankton and zooplankton support populations of fish and whales. Nutrients are scarce and this is a relatively less productive part of the marine biome. When photosynthetic organisms and the organisms that feed on them die, their bodies fall to the bottom of the ocean where they remain; the open ocean lacks a process for bringing the organic nutrients back up to the surface.

Beneath the pelagic zone is the benthic realm, the deepwater region beyond the continental shelf (Figure 6.3.2). The bottom of the benthic realm is comprised of sand, silt, and dead organisms. Temperature decreases as water depth increases. This is a nutrient-rich portion of the ocean because of the dead organisms that fall from the upper layers of the ocean. Because of this high level of nutrients, a diversity of fungi, sponges, sea anemones, marine worms, sea stars, fishes, and bacteria exists.

The deepest part of the ocean is the abyssal zone, which is at depths of 4000 m or greater. The abyssal zone (Figure 6.3.2) is very cold and has very high pressure, high oxygen content, and low nutrient content. There are a variety of invertebrates and fishes found in this zone, but the abyssal zone does not have photosynthetic organisms. Chemosynthetic bacteria use the hydrogen sulfide and other minerals emitted from deep hydrothermal vents. These chemosynthetic bacteria use the hydrogen sulfide as an energy source and serve as the base of the food chain found around the vents.

ART CONNECTION

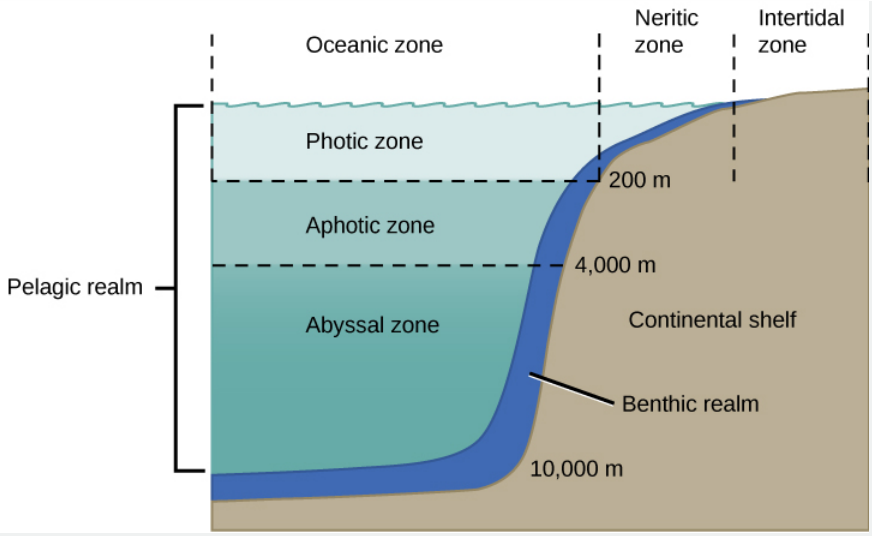


Figure 6.3.2**:** The ocean is divided into different zones based on water depth, distance from the shoreline, and light penetration.

In which of the following regions would you expect to find photosynthetic organisms?

A. The aphotic zone, the neritic zone, the oceanic zone, and the benthic realm.
B. The photic zone, the intertidal zone, the neritic zone, and the oceanic zone.
C. The photic zone, the abyssal zone, the neritic zone, and the oceanic zone.
D. The pelagic realm, the aphotic zone, the neritic zone, and the oceanic zone.

Coral Reefs

Coral reefs are ocean ridges formed by marine invertebrates living in warm shallow waters within the photic zone of the ocean. They are found within 30˚ north and south of the equator. The Great Barrier Reef is a well-known reef system located several miles off the northeastern coast of Australia. Other coral reefs are fringing islands, which are directly adjacent to land, or atolls, which are circular reefs surrounding a former island that is now underwater. The coral-forming colonies of organisms (members of phylum Cnidaria) secrete a calcium carbonate skeleton. These calcium-rich skeletons slowly accumulate, thus forming the underwater reef (Figure 6.3.3). Corals found in shallower waters (at a depth of approximately 60 m or about 200 ft) have a mutualistic relationship with photosynthetic unicellular protists. The relationship provides corals with the majority of the nutrition and the energy they require. The waters in which these corals live are nutritionally poor and, without this mutualism, it would not be possible for large corals to grow because there are few planktonic organisms for them to feed on. Some corals living in deeper and colder water do not have a mutualistic relationship with protists; these corals must obtain their energy exclusively by feeding on plankton using stinging cells on their tentacles.

CONCEPT IN ACTION

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

Coral reefs are one of the most diverse biomes. It is estimated that more than 4000 fish species inhabit coral reefs. These fishes can feed on coral, the cryptofauna (invertebrates found within the calcium carbonate structures of the coral reefs), or the seaweed and algae that are associated with the coral. These species include predators, herbivores, or planktivores. Predators are animal species that hunt and are carnivores or “flesh eaters.” Herbivores eat plant material, and planktivores eat plankton.



Figure 6.3.3**:** Coral reefs are formed by the calcium carbonate skeletons of coral organisms, which are marine invertebrates in the phylum Cnidaria. (credit: Terry Hughes)

EVOLUTION IN ACTION: Global Decline of Coral Reefs

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

Together, climate change and human activity pose dual threats to the long-term survival of the world's coral reefs. The main cause of killing of coral reefs is warmer-than-usual surface water. As global warming raises ocean temperatures, coral reefs are suffering. The excessive warmth causes the coral organisms to expel their endosymbiotic, food-producing protists, resulting in a phenomenon known as bleaching. The colors of corals are a result of the particular protist endosymbiont, and when the protists leave, the corals lose their color and turn white, hence the term "bleaching."

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

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

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

Although a rise in global temperatures of 1°C–2°C (a conservative scientific projection) in the coming decades may not seem large, it is very significant to this biome. When change occurs rapidly, species can become extinct before evolution leads to newly adapted species. Many scientists believe that global warming, with its rapid (in terms of evolutionary time) and

inexorable increases in temperature, is tipping the balance beyond the point at which many of the world's coral reefs can recover.

Estuaries: Where the Ocean Meets Fresh Water

Estuaries are biomes that occur where a river, a source of fresh water, meets the ocean. Therefore, both fresh water and salt water are found in the same vicinity; mixing results in a diluted (brackish) salt water. Estuaries form protected areas where many of the offspring of crustaceans, mollusks, and fish begin their lives. Salinity is an important factor that influences the organisms and the adaptations of the organisms found in estuaries. The salinity of estuaries varies and is based on the rate of flow of its freshwater sources. Once or twice a day, high tides bring salt water into the estuary. Low tides occurring at the same frequency reverse the current of salt water (Figure 6.3.4).



Figure 6.3.4**:** As estuary is where fresh water and salt water meet, such as the mouth of the Klamath River in California, shown here. (credit: U.S. Army Corps of Engineers)

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

Freshwater Biomes

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

Lakes and Ponds

Lakes and ponds can range in area from a few square meters to thousands of square kilometers. Temperature is an important abiotic factor affecting living things found in lakes and ponds. During the summer in temperate regions, thermal stratification of deep lakes occurs when the upper layer of water is warmed by the Sun and does not mix with deeper, cooler water. The process produces a

sharp transition between the warm water above and cold water beneath. The two layers do not mix until cooling temperatures and winds break down the stratification and the water in the lake mixes from top to bottom. During the period of stratification, most of the productivity occurs in the warm, well-illuminated, upper layer, while dead organisms slowly rain down into the cold, dark layer below where decomposing bacteria and cold-adapted species such as lake trout exist. Like the ocean, lakes and ponds have a photic layer in which photosynthesis can occur. Phytoplankton (algae and cyanobacteria) are found here and provide the base of the food web of lakes and ponds. Zooplankton, such as rotifers and small crustaceans, consume these phytoplankton. At the bottom of lakes and ponds, bacteria in the aphotic zone break down dead organisms that sink to the bottom.

Nitrogen and particularly phosphorus are important limiting nutrients in lakes and ponds. Therefore, they are determining factors in the amount of phytoplankton growth in lakes and ponds. When there is a large input of nitrogen and phosphorus (e.g., from sewage and runoff from fertilized lawns and farms), the growth of algae skyrockets, resulting in a large accumulation of algae called an algal bloom. Algal blooms (Figure 6.3.5) can become so extensive that they reduce light penetration in water. As a result, the lake or pond becomes aphotic and photosynthetic plants cannot survive. When the algae die and decompose, severe oxygen depletion of the water occurs. Fishes and other organisms that require oxygen are then more likely to die.



Figure 6.3.5**:** The uncontrolled growth of algae in this waterway has resulted in an algal bloom.

Rivers and Streams

Rivers and the narrower streams that feed into the rivers are continuously moving bodies of water that carry water from the source or headwater to the mouth at a lake or ocean. The largest rivers include the Nile River in Africa, the Amazon River in South America, and the Mississippi River in North America (Figure 6.3.6).



(a) (b)

Figure 6.3.6**:** Rivers range from (a) narrow and shallow to (b) wide and slow moving. (credit a: modification of work by Cory Zanker; credit b: modification of work by David DeHetre)

Abiotic features of rivers and streams vary along the length of the river or stream. Streams begin at a point of origin referred to as source water. The source water is usually cold, low in nutrients, and clear. The channel (the width of the river or stream) is narrower here than at any other place along the length of the river or stream. Headwater streams are of necessity at a higher elevation than the mouth of the river and often originate in regions with steep grades leading to higher flow rates than lower elevation stretches of the river.

Faster-moving water and the short distance from its origin results in minimal silt levels in headwater streams; therefore, the water is clear. Photosynthesis here is mostly attributed to algae that are growing on rocks; the swift current inhibits the growth of phytoplankton. Photosynthesis may be further reduced by tree cover reaching over the narrow stream. This shading also keeps temperatures lower. An additional input of energy can come from leaves or other organic material that falls into a river or stream from the trees and other plants that border the water. When the leaves decompose, the organic material and nutrients in the leaves are returned to the water. The leaves also support a food chain of invertebrates that eat them and are in turn eaten by predatory invertebrates and fish. Plants and animals have adapted to this fast-moving water. For instance, leeches (phylum Annelida) have elongated bodies and suckers on both ends. These suckers attach to the substrate, keeping the leech anchored in place. In temperate regions, freshwater trout species (phylum Chordata) may be an important predator in these fast-moving and colder river and streams.

As the river or stream flows away from the source, the width of the channel gradually widens, the current slows, and the temperature characteristically increases. The increasing width results from the increased volume of water from more and more tributaries. Gradients are typically lower farther along the river, which accounts for the slowing flow. With increasing volume can come increased silt, and as the flow rate slows, the silt may settle, thus increasing the deposition of sediment. Phytoplankton can also be suspended in slow-moving water. Therefore, the water will not be as clear as it is near the source. The water is also warmer as a result of longer exposure to sunlight and the absence of tree cover over wider expanses between banks. Worms (phylum Annelida) and insects (phylum Arthropoda) can be found burrowing into the mud. Predatory vertebrates (phylum Chordata) include waterfowl, frogs, and fishes. In heavily silt-laden rivers, these predators must find food in the murky waters, and, unlike the trout in the clear waters at the source, these vertebrates cannot use vision as their primary sense to find food. Instead, they are more likely to use taste or chemical cues to find prey.

When a river reaches the ocean or a large lake, the water typically slows dramatically and any silt in the river water will settle. Rivers with high silt content discharging into oceans with minimal currents and wave action will build deltas, low-elevation areas of sand and mud, as the silt settles onto the ocean bottom. Rivers with low silt content or in areas where ocean currents or wave action are high create estuarine areas where the fresh water and salt water mix.

Wetlands

Wetlands are environments in which the soil is either permanently or periodically saturated with water. Wetlands are different from lakes and ponds because wetlands exhibit a near continuous cover of emergent vegetation. Emergent vegetation consists of wetland

plants that are rooted in the soil but have portions of leaves, stems, and flowers extending above the water's surface. There are several types of wetlands including marshes, swamps, bogs, mudflats, and salt marshes (Figure 6.3.7).



Figure 6.3.7: Located in southern Florida, Everglades National Park is a vast array of wetland environments, including sawgrass marshes, cypress swamps, and estuarine mangrove forests. Here, a great egret walks among cypress trees. (credit: NPS)

Freshwater marshes and swamps are characterized by slow and steady water flow. Bogs develop in depressions where water flow is low or nonexistent. Bogs usually occur in areas where there is a clay bottom with poor percolation. Percolation is the movement of water through the pores in the soil or rocks. The water found in a bog is stagnant and oxygen depleted because the oxygen that is used during the decomposition of organic matter is not replaced. As the oxygen in the water is depleted, decomposition slows. This leads to organic acids and other acids building up and lowering the pH of the water. At a lower pH, nitrogen becomes unavailable to plants. This creates a challenge for plants because nitrogen is an important limiting resource. Some types of bog plants (such as sundews, pitcher plants, and Venus flytraps) capture insects and extract the nitrogen from their bodies. Bogs have low net primary productivity because the water found in bogs has low levels of nitrogen and oxygen.

Section Summary

Aquatic biomes include both saltwater and freshwater biomes. The abiotic factors important for the structuring of aquatic biomes can be different than those seen in terrestrial biomes. Sunlight is an important factor in bodies of water, especially those that are very deep, because of the role of photosynthesis in sustaining certain organisms. Other important factors include temperature, water movement, and salt content. Oceans may be thought of as consisting of different zones based on water depth, distance from the shoreline, and light penetrance. Different kinds of organisms are adapted to the conditions found in each zone. Coral reefs are unique marine ecosystems that are home to a wide variety of species. Estuaries are found where rivers meet the ocean; their shallow waters provide nourishment and shelter for young crustaceans, mollusks, fishes, and many other species. Freshwater biomes include lakes, ponds, rivers, streams, and wetlands. Bogs are an interesting type of wetland characterized by standing water, a lower pH, and a lack of nitrogen.

Art Connections

Figure 6.3.2: In which of the following regions would you expect to find photosynthetic organisms?

A. The aphotic zone, the neritic zone, the oceanic zone, and the benthic realm.
B. The photic zone, the intertidal zone, the neritic zone, and the oceanic zone.
C. The photic zone, the abyssal zone, the neritic zone, and the oceanic zone.
D. The pelagic realm, the aphotic zone, the neritic zone, and the oceanic zone.

Answer

B. The photic zone, the intertidal zone, the neritic zone, and the oceanic zone.

Glossary

abyssal zone
the deepest part of the ocean at depths of 4000 m or greater

algal bloom
a rapid increase of algae in an aquatic system

aphotic zone
the part of the ocean where photosynthesis cannot occur

benthic realm
(also, benthic zone) the part of the ocean that extends along the ocean bottom from the shoreline to the deepest parts of the ocean floor

channel
the bed and banks of a river or stream

coral reef
an ocean ridge formed by marine invertebrates living in warm shallow waters within the photic zone

cryptofauna
the invertebrates found within the calcium carbonate substrate of coral reefs

ecosystem services
the human benefits provided by natural ecosystems

emergent vegetation
the plants living in bodies of water that are rooted in the soil but have portions of leaves, stems, and flowers extending above the water's surface

estuary
a region where fresh water and salt water mix where a river discharges into an ocean or sea

intertidal zone
the part of the ocean that is closest to land; parts extend above the water at low tide

neritic zone
the part of the ocean that extends from low tide to the edge of the continental shelf

oceanic zone
the part of the ocean that begins offshore where the water measures 200 m deep or deeper

pelagic realm
(also, pelagic zone) the open ocean waters that are not close to the bottom or near the shore

photic zone
the upper layer of ocean water in which photosynthesis is able to take place

planktivore
an animal that eats plankton

source water

the point of origin of a river or stream

wetland

environment in which the soil is either permanently or periodically saturated with water

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CHAPTER OVERVIEW

7: Food and Agriculture

7.1: Food Security
7.2: Food and Nutrients
7.3: Defining Nutrition, Health, and Disease
7.4: Soil Profiles and Processes
7.5: Soil-Plant Interactions
7.6: Conventional Agriculture
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7.1: Food Security

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

From Agriculture to Food Security

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

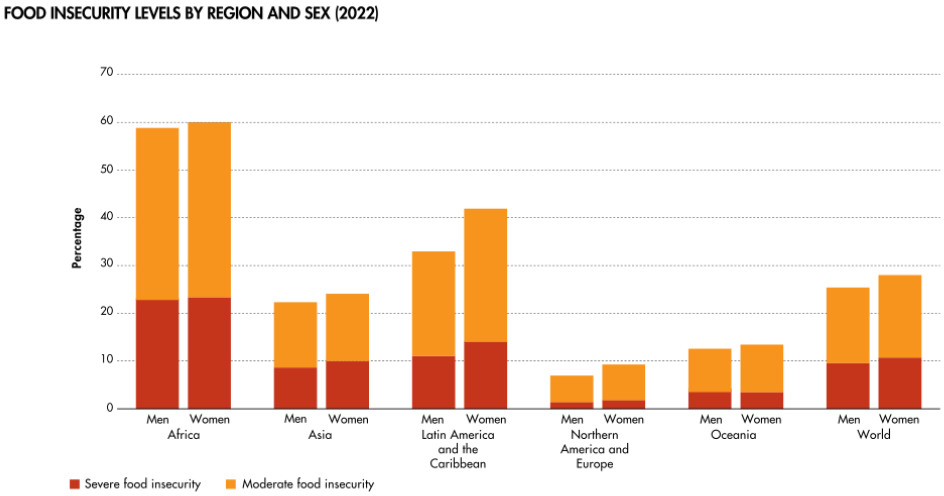
When food security is analyzed at the national level, an understanding not only of national production is important, but also of the country's **access** to food from the global market, its foreign exchange earnings, and its citizens' consumer choices. Food security analyzed at the household level is 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.



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Obesity

Obesity means having too much body fat. It is not the same as overweight, which means weighing too much. 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. 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 7.1.1).

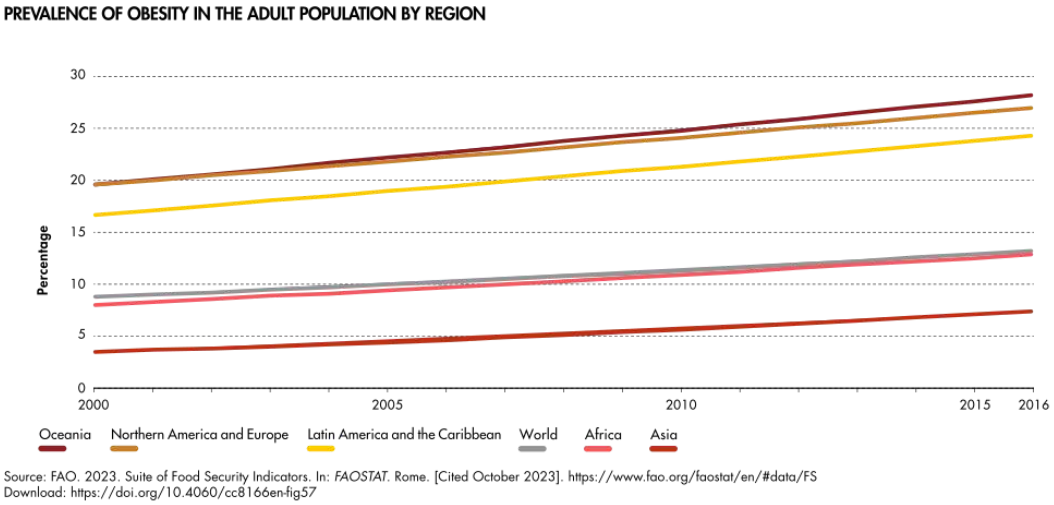
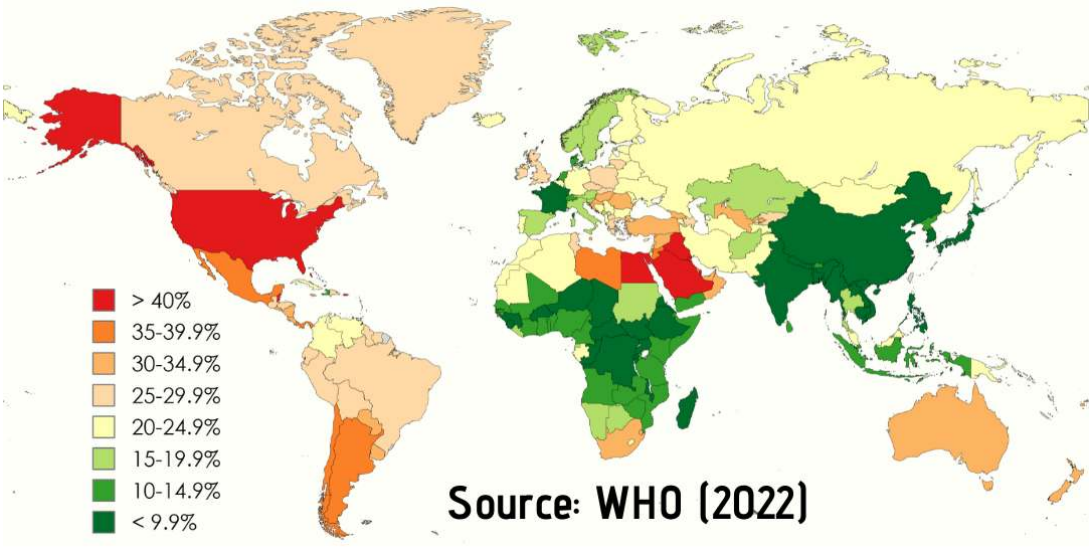


Figure 7.1.1. Obesity by region.

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Rates of Obesity by Region



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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. *National Geographic*. February. (Update 10/12/2025: This article requires paid access)

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7.2: 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 in Table below.

Table 7.2.1: 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

- Includes water in foods as well as beverages

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 MyPyramid and nutrition labels on food packages.

MyPyramid

MyPyramid was developed by the U.S. Food and Drug Administration. It shows how much you should eat each day of foods in different food groups. MyPyramid is shown in **Figure** below. You can visit the MyPyramid.gov website for more details or to customize MyPyramid for your gender, age, activity level, and other factors.



Figure 7.2.1: MyPyramid is visual representation of how much you should eat each day of foods in different food groups.

Guidelines for Using MyPyramid

1. The six colored bands represent six food groups:

- Brown = Grains—At least half should be whole grains.
- Green = Vegetables—Choose a variety of vegetables, including dark green and orange vegetables, dry beans and peas.
- Red = Fruits—Include a variety of fruits, and consume whole fruits instead of fruit juices.
- Yellow = Oils—Choose mainly unsaturated nut and vegetable oils.
- Blue = Milk—Dairy products should be low-fat or fat-free choices.
- Purple = Meat and Beans—Choose fish and low-fat meats, as well as beans, peas, nuts, and seeds.

2. The width of each colored band shows the proportion of food that should come from each food group.

3. The figure climbing stairs reminds you to balance food with exercise: 30–60 min/day of moderate-to-vigorous activity is recommended for most people.

Each food group represented by a colored band in MyPyramid is a good source of nutrients. The wider the band, the more you should eat from that food group. For example, the brown band is widest, so the largest proportion of foods should come from the

grains group. The white tip of MyPyramid represents foods that should be eaten only in very small amounts or very infrequently. They include foods such as ice cream and potato chips that contain few nutrients and may contribute excess kilocalories to the diet.

The figure “walking” up the side of MyPyramid in **Figure** above represents the role of exercise in balanced eating. Daily exercise helps you burn any extra energy that you consume in foods. The more active you are, the more energy you use. Light activities, such as golfing, typically use only a few hundred kilocalories per hour. Strenuous activities, such as running, may use over 900 kilocalories per hour.

Harvard University recently developed an alternative healthy eating pyramid, which is shown in **Figure** below. It differs from MyPyramid in placing more emphasis on exercise and a greater focus on eating fruits, vegetables, and healthy plant oils. It moves red meats and starchy, low-nutrient foods, such as white bread and white rice, to the category of foods to eat in very limited amounts. Some experts think that the Harvard pyramid is less confusing than MyPyramid and represents an even healthier way of eating.

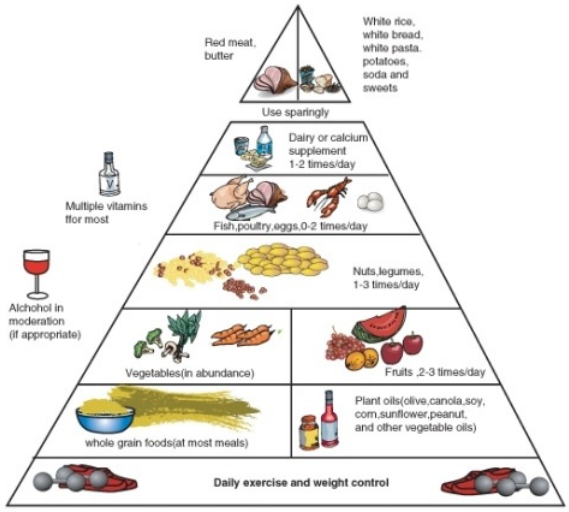


Figure 7.2.2: Healthy eating pyramid.

MyPlate

In June 2011, the United States Department of Agriculture replaced My Pyramid with **MyPlate.** MyPlate depicts the relative portions of various food groups. See http://www.choosemyplate.gov/ for further information.



Figure 7.2.3: MyPlate is a visual guideline for balanced eating, replacing MyPyramid in 2011.

The following guidelines accompany MyPlate:

1. Balancing Calories

- Enjoy your food, but eat less.
- Avoid oversized portions.

2. Foods to Increase

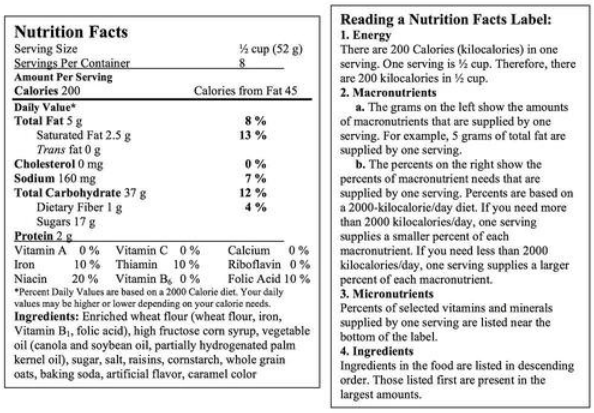
- Make half your plate fruits and vegetables.
- Make at least half your grains whole grains.
- Switch to fat-free or low-fat (1%) milk.

3. Foods to Reduce

- Compare sodium in foods like soup, bread, and frozen meals — and choose the foods with lower numbers.
- Drink water instead of sugary drinks.

Food Labels

Packaged foods are required by law to carry a nutrition facts label, like the one in **Figure** below, showing the nutrient content and ingredients in the food.



Nutrition Facts

Serving Size	½ cup (52 g)
Servings Per Container	8
Amount Per Serving	
Calories 200	Calories from Fat 45
Daily Value*	
Total Fat 5 g	**8 %**
Saturated Fat 2.5 g	**13 %**
Trans fat 0 g	
Cholesterol 0 mg	**0 %**
Sodium 160 mg	**7 %**
Total Carbohydrate 37 g	**12 %**
Dietary Fiber 1 g	**4 %**
Sugars 17 g	
Protein 2 g	

Vitamin A	0 %	Vitamin C	0 %	Calcium	0 %
Iron	10 %	Thiamin	10 %	Riboflavin	0 %
Niacin	20 %	Vitamin B_6	0 %	Folic Acid	10 %

*Percent Daily Values are based on a 2000 Calorie diet. Your daily values may be higher or lower depending on your calorie needs.

Ingredients: Enriched wheat flour (wheat flour, iron, Vitamin B_1, folic acid), high fructose corn syrup, vegetable oil (canola and soybean oil, partially hydrogenated palm kernel oil), sugar, salt, raisins, cornstarch, whole grain oats, baking soda, artificial flavor, caramel color

Reading a Nutrition Facts Label:

1. Energy
There are 200 Calories (kilocalories) in one serving. One serving is ½ cup. Therefore, there are 200 kilocalories in ½ cup.

2. Macronutrients

a. The grams on the left show the amounts of macronutrients that are supplied by one serving. For example, 5 grams of total fat are supplied by one serving.

b. The percents on the right show the percents of macronutrient needs that are supplied by one serving. Percents are based on a 2000-kilocalorie/day diet. If you need more than 2000 kilocalories/day, one serving supplies a smaller percent of each macronutrient. If you need less than 2000 kilocalories/day, one serving supplies a larger percent of each macronutrient.

3. Micronutrients
Percents of selected vitamins and minerals supplied by one serving are listed near the bottom of the label.

4. Ingredients
Ingredients in the food are listed in descending order. Those listed first are present in the largest amounts.

Figure 7.2.4: Nutrition facts label.

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:

Food A	Food B
15g/300 kcal = 0.05 g/kcal Nutrient Density: Energy: 300 kval Protein: 15 g	10g/120 kcal = 0.08 g/kcal Nutrient Density: Energy: 120 kval 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 7.2.2: 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
(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** 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 7.2.2: 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
(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. They occur primarily in colorful fruits and vegetables, like those shown in **Figure** below.



Figure 7.2.5: Good sources of phytochemicals.

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 (**Figure** bellow), have proven to be powerful antioxidants.



Figure 7.2.6: Berries and Cherries

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7.3: Defining Nutrition, Health, and Disease

Learning Objective

- Explain the terms nutrition, health, health promotion, and disease prevention.

You and I are bombarded with images and messages about food everywhere we go. We see super models eating giant burgers, chefs battling to prepare meals, and the top places to burst your belly from consuming atomic chicken wings and deli sandwiches longer than a foot. There are also shows that feature bizarre foods from cultures around the world. How do you use the information from popular network food shows to build a nutritious meal? You don't—these shows are for entertainment. The construction of a nutritious meal requires learning about which foods are healthy and which foods are not-so-health, how foods and nutrients function in your body, and how to use scientific resources to make healthful choices for you and those you care about. This text is designed to provide you with the information necessary to make sound nutritional choices that will optimize health and help prevent disease.



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How do you fill your plate?

The word nutrition first appeared in 1551 and comes from the Latin word *nutrire*, meaning "to nourish." Today, we define Nutritional science is the investigation of how an organism is nourished, and incorporates the study of how nourishment affects personal health, population health, and planetary health. Nutritional science covers a wide spectrum of disciplines. As a result, nutritional scientists can specialize in particular aspects of nutrition such as biology, physiology, immunology, biochemistry, education, psychology, sustainability, and sociology.

Without adequate nutrition the human body does not function optimally, and severe nutritional inadequacy can lead to disease and even death. The typical American diet is lacking in many ways, from not containing the proper amounts of essential nutrients, to being too speedily consumed, to being only meagerly satisfying. Dietitians are nutrition professionals who integrate their knowledge of nutritional science into helping people achieve a healthy diet and develop good dietary habits. The Academy of Nutrition and Dietetics (AND) is the largest organization of nutrition professionals worldwide and dietitians registered with the AND are committed to helping Americans eat well and live healthier lives. To learn more from the AND's nutritional advice, visit EatRight.Org

Your ability to wake up, to think clearly, to communicate, to hope, to dream, to go to school, to gain knowledge, to go to work, to earn a living, and to do all of the things that you like to do are dependent upon one factor—your health. Good health means you are able to function normally and work hard to achieve your goals in life. For the next few minutes, take some time to view snapshots of the insides of the refrigerators of American mechanics, doctors, school teachers, hunters, short-order cooks, college students, vegans, and more. Visit Mark Menjivar's portrait exhibition, "You Are What You Eat". Menjivar hopes these images will invoke new thoughts about, "How we care for our bodies. How we care for others. And how we care for the land." As you look at these

images think about your personal health, the health of your family and friends, and the health of this planet. These hopes encompass the inspirations for this book.

https://bio.libretexts.org/@go/page/162433

Interactive 1.1

Mark Menjivar has traveled around the United States taking photographs of the contents of refrigerators of numerous types of people. The portraits are available for viewing on his website under “You Are What You Eat.” Then click on "Refrigerators" on the left.

Nutrition and Health and Disease

In 1946, the World Health Organization (WHO) defined health as “a state of complete physical, mental, and social well-being, and not merely the absence of disease or infirmity.” This definition was adopted into the WHO constitution in 1948 and has not been amended since. A triangle is often used to depict the equal influences of physical, mental, and social well-being on health (Figure 1.1). Disease is defined as any abnormal condition affecting the health of an organism, and is characterized by specific signs and symptoms. Signs refer to identifying characteristics of a disease such as swelling, weight loss, or fever. Symptoms are the features of a disease recognized by a patient and/or their doctor. Symptoms can include nausea, fatigue, irritability, and pain. Diseases are broadly categorized as resulting from pathogens (i.e., bacteria, viruses, fungi, and parasites), deficiencies, genetics, and physiological dysfunction. Diseases that primarily affect physical health are those that impair body structure (as is the case with osteoporosis), or functioning (as is the case with cardiovascular disease). Mental illnesses primarily affect mental and social well-being.

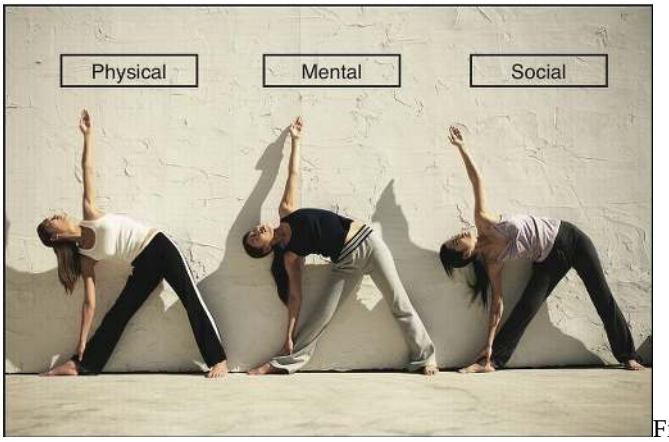


Figure 7.3.1: The Health Triangle. © Thinkstock

The foods we eat affect all three aspects of our health. For example, a teen with Type 2 diabetes (a disease often brought on by poor diet) is first diagnosed by physical signs and symptoms such as increased urination, thirstiness, and unexplained weight loss. But research has also found that teens with Type 2 diabetes have impaired thinking and do not interact well with others in school, thereby affecting mental and social well-being. Type 2 diabetes is just one example of a physiological disease that affects all aspects of health—physical, mental, and social.

Public Health and Disease Prevention

In 1894, the first congressional funds were appropriated to the US Department of Agriculture (USDA) for the study of the relationship between nutrition and human health. Dr. Wilbur Olin Atwater was appointed as the Chief of Nutrition Investigations and is regarded as the “Father of Nutrition Science” in America. Under his guidance, the USDA released the first bulletin to the American public that contained information on the amounts of fat, carbohydrates, proteins, and food energy in various foods. Nutritional science advanced considerably in these early years, but it took until 1980 for the USDA and the US Department of Health and Human Services (HHS) to jointly release the first edition of *Nutrition and Your Health: Dietary Guidelines for Americans*.

Although wide distribution of the "Dietary Guidelines for Americans" did not come about until the 1980s, many historical events that demonstrated the importance of diet to health preceded their release. Assessments of the American diet in the 1930s led President Franklin D. Roosevelt to declare in his inaugural address on January 20, 1937, “I see one-third of our nation is ill-housed, ill-clad, and ill-nourished.” From the time of Atwater until the onset of the Great Depression, nutrition scientists had discovered many of the vitamins and minerals that are essential for the functioning of the human body. Their work and the acknowledgement

by President FDR of the nutritional inadequacy of the American diet evoked a united response between scientists and government, leading to: the enrichment of flour (adding vitamins and minerals), the development of free or reduced-cost school lunch programs, and advancements of nutrition education in this country.

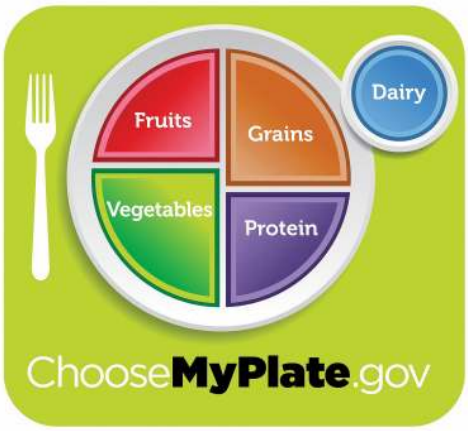


Figure 1.2: The Federal Government's New and Improved Tool of Nutritional Communication

In the latter part of the twentieth century nutrition scientists, public health organizations, and the American public increasingly recognized that eating too much of certain foods is linked to chronic diseases. We now know that diet-related conditions and diseases include: hypertension (high blood pressure), obesity, Type 2 diabetes, cardiovascular disease, some cancers, and osteoporosis. These diet-related conditions and diseases are some of the biggest killers of Americans. The United States Department of Health and Human Services (HHS) reports that unhealthy diets and inactivity cause between 310,000 and 580,000 deaths every single year. According to the United States Department of Agriculture (USDA), eating healthier could save Americans over $70 billion per year and this does not include the cost of obesity, which is estimated to cost a further $117 billion per year. Unfortunately, despite the fact that the prevalence of these diseases can be decreased by healthier diets and increased physical activity, the Center for Disease Control (CDC) reports that the federal government spends one thousand times more to treat disease than to prevent it ($1,390 versus $1.21 per person each year). In 2015, the newest edition of the Dietary Guidelines for Americans identified obesity as the number one nutritional-related health problem in the United States and established strategies to combat its incidence and health consequences in the American population. A 2008 study in the journal Obesity reported that if current trends are not changed, 100 percent of Americans will be overweight or obese in 2048! Wang Y, et al. "Will All Americans Become Overweight or Obese? Estimating the Progression and Cost of the US Obesity Epidemic." Obesity 10, no. 16 (October 2008): 2323–30. http://www.nature.com/oby/journal/v16/n10/full/oby2008351a.html In 2011, the US federal government released a new multimedia tool that aims to help Americans choose healthier foods from the five food groups (grains, vegetables, fruits, dairy, and proteins). The tool, called "Choose MyPlate," is available at choosemyplate.gov.

Key Takeaways

- Health is defined as "a state of complete physical, mental, and social well-being, and not merely the absence of disease or infirmity." World Health Organization.
- Disease is defined as any abnormal condition that affects the health of an organism, and is characterized by specific signs and symptoms.
- Disease affects all three aspects of the health triangle.
- Good nutrition provides a mechanism to promote health and prevent disease.
- Diet-related conditions and diseases include: obesity, Type 2 diabetes, cardiovascular disease, some cancers, and osteoporosis.
- It took until the 1980s for the US federal government to develop a diet-related public policy designed to equip Americans with the tools to change to a healthier diet.

Discussion Starters

1. How might the way we nourish our bodies affect planetary health?
2. Debate your classmates: Should the federal government be concerned with what Americans eat?

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7.4: 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 7.4.1). 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.

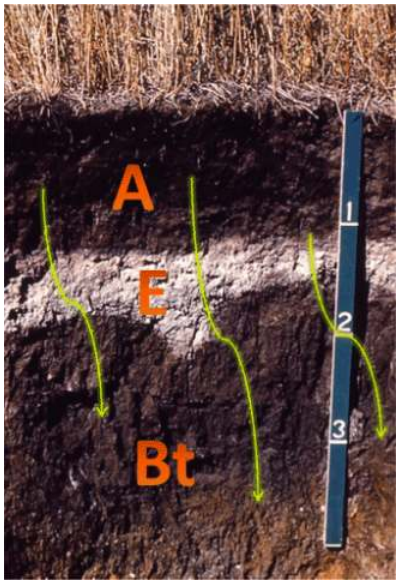


Figure 7.4.1. Soil Profile. Photograph shows a soil profile from South Dakota with A, E, and Bt horizons. The yellow arrows symbolize translocation of fine clays to the Bt horizon. The scale is in feet. Source: University of Idaho and modified by D. Grimley.

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 7.4.2) 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.

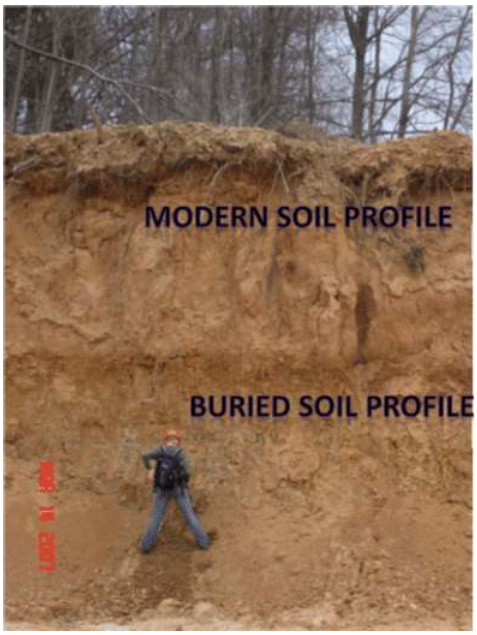


Figure 7.4.2. Modern versus Buried Soil Profiles. A buried soil profile, or paleosol (above geologist ‘s head), represents soil development during the last interglacial period. A modern soil profile (Alfisol) occurs near the land surface. Source: D. Grimley.

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 7.4.3).

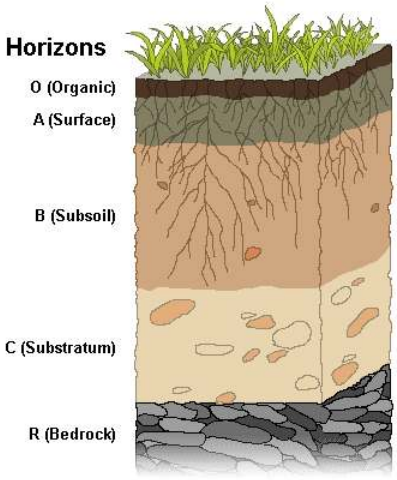


Figure 7.4.3. This images shows the different horizons, or layers, in soil. *This work by Wilsonbiggs is licensed under CC BY-SA 4.0*

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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7.5: 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 7.5.1). 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.

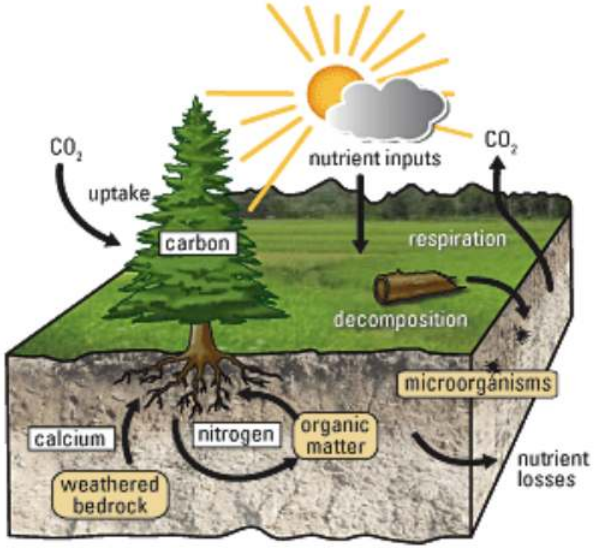


Figure 7.5.1. Soil-Plant Nutrient Cycle. This figure illustrates the uptake of nutrients by plants in the forest-soil ecosystem. Source: U.S. Geological Survey.

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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7.6: Conventional Agriculture

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



Figure 7.6.1. Conventional agriculture is dependent on large investments in mechanized equipment powered mostly by fossil fuels. This has made agriculture efficient, but has had an impact on the environment. *Cotton Harvest by Kimberly Vardeman is licensed under CC BY 4.0.*

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

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

Ecological Concerns

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

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

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

due to overuse of surface and ground water for irrigation with little concern for the natural cycle that maintains stable water availability.

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

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

Economic and Social Concerns

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

Economic pressures have led to a tremendous loss to the number of farms, particularly small farms, and farmers during the past few decades. More than 155,000 farms were lost from 1987 to 1997. Economically, it is very difficult for potential farmers to enter the business today because of the high cost of doing business. Productive farmland also has been swallowed up by urban and suburban sprawl—since 1970, over 30 million acres have been lost to development.

Impacts on Human Health

Many potential health hazards are tied to farming practices. The general public may be affected by the sub-therapeutic use of antibiotics in animal production and the contamination of food and water by pesticides and nitrates. These are areas of active research to determine the levels of risk. The health of farm workers is also of concern, as their risk of exposure is much higher.

Philosophical Considerations

Historically, farming played an important role in our development and identity as a nation. From strongly agrarian roots, we have evolved into a culture with few farmers. Less than two percent of Americans now produce food for all U.S. citizens. Can sustainable and equitable food production be established when most consumers have so little connection to the natural processes that produce their food? What intrinsically American values have changed and will change with the decline of rural life and farmland ownership?

World population continues to grow. According to recent United Nations population projections, the world population will grow to 9.7 billion in 2050 and 11.2 billion in 2100. The rate of population increase is especially high in many developing countries. In these countries, the population factor, combined with rapid industrialization, poverty, political instability, and large food imports and debt burden, make long-term food security especially urgent.

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7.7: 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 7.7.1). 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 7.7.1. 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 7.7.2). 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 7.7.2. 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 7.7.3).



Figure 7.7.3. 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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7.8: What is Permaculture?

In this book, basic information is given to get you started. Firstly, we look at the definition of Permaculture with a bit of history of the word. Secondly, we look at the overall design process and fields of study that inform Permaculture. Finally, we look at the four part Permaculture Decision Making Matrix which is the basis of the information in this book.



Permaculture Definition

It’s time to get started learning about Permaculture! In this first video of the book, we define the word, and talk about it’s origins.





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- Intro to Permaculture: What is Permaculture? – Video Transcript
- Introdução a Permacultura: O que e Permacultura – Tradução Português

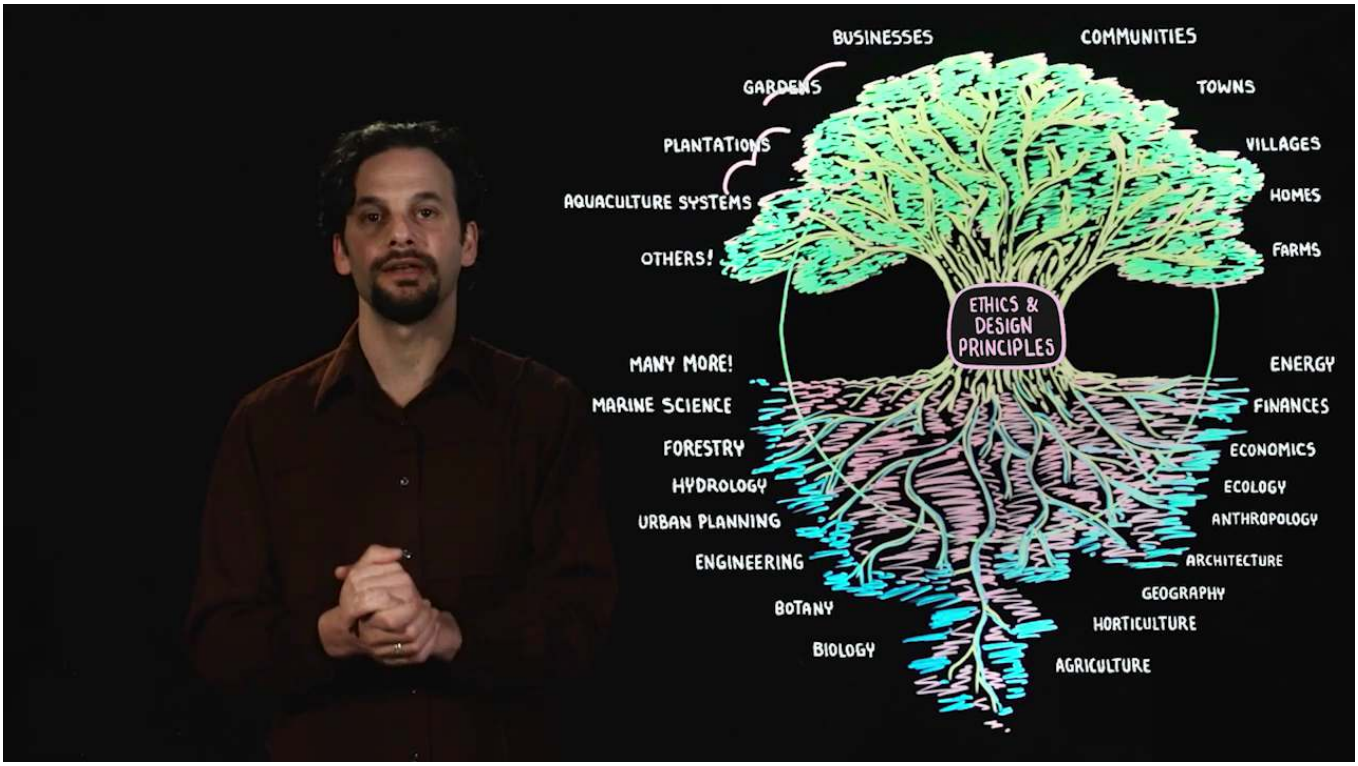
Featured Links

- The Definition of Permaculture: An Interview with Bill Mollison
- Wikipedia Permaculture Definition

In the video above, we make reference to Permaculture's co-founder, Bill Mollison. You can read an interview with Bill in the featured links provided above where he talks about the Permaculture definition. We also make reference to water, food and shelter systems. **A system is defined as "a set of connected things or parts forming a complex whole."** So when we refer to water systems, we're recognizing that the way we design for water on a Permaculture site takes into account its' many interconnections, with soils, trees, water tables, the atmosphere, and wildlife.

Permaculture Design Process

We're going to look now at the overall process of the Permaculture design system. Permaculture is multidisciplinary and multi-faceted, which makes Permaculture very dynamic, but also makes it hard to define. This video explains the wide array of influences and outputs of Permaculture design.





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- Intro to Permaculture: The Foundations of Permaculture Design – Video Transcript
- Introdução a Permacultura: As Fundações do Projeto de Permacultura – Tradução Português

Featured Links

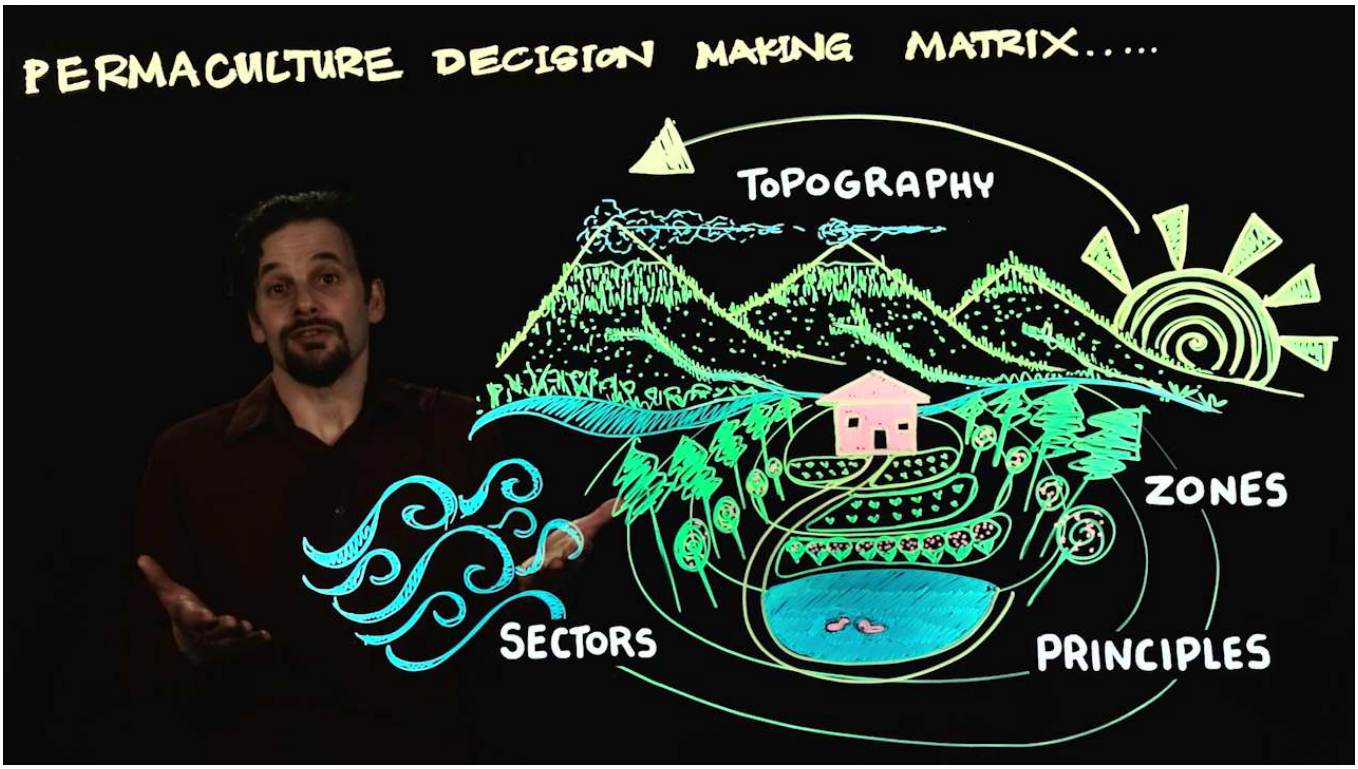
- Holmgren's Permaculture Flower

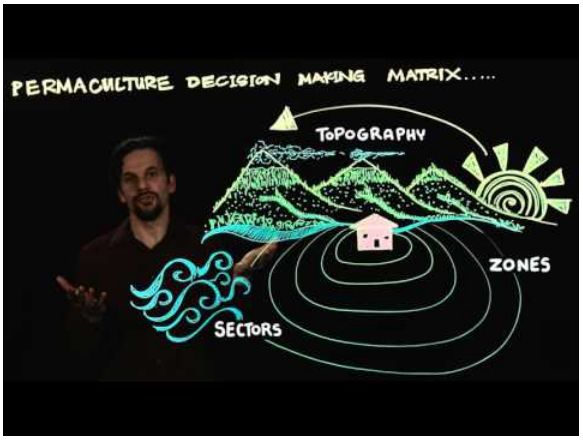
This video unites a number of diagrams that have been circulating Permaculture design course texts and media outlets for many years, including David Holmgren's Permaculture Flower (link located in the featured links above). You will notice many analogies

to a tree in this book, as the form of a tree provides so many opportunities to understand how nature works and how the Permaculture design system is modeled after nature.

Permaculture Decision-Making Matrix

This video consolidates the Permaculture design process into four distinct parts: topography, sectors, zones and principles. These are the major topics we will be looking at in this short introductory book.





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- Intro to Permaculture: Permaculture Decision Making Matrix – Video Transcript
- Introdução a Permacultura: A Matriz de Tomar uma Decisão na Permacultura – Tradução Português

The Permaculture decision-making matrix is a term and structure coined by Andrew Millison, but only represents a repackaging of Permaculture design process that is explained by Bill Mollison and many great teachers and practitioners. This decision making tool is useful as a basic outline of the main tools used in Permaculture design.

Image Sources

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7.9: Pests and Pesticides

Pests are organisms that occur where they are not wanted or that cause damage to crops or humans or other animals. Thus, the term "pest" is a highly subjective term. A **pesticide** is a term for any substance intended for preventing, destroying, repelling, or mitigating any pest. Though often misunderstood to refer only to insecticides, the term pesticide also applies to herbicides, fungicides, and various other substances used to control pests. By their very nature, most pesticides create some risk of harm—pesticides can cause harm to humans, animals, and/or the environment because they are designed to kill or otherwise adversely affect living things. At the same time, pesticides are useful to society because they can kill potential disease-causing organisms and control insects, weeds, worms, and fungi.



Figure 7.9.1. The cotton boll weevil is considered a major pest because of the damage it does to cotton plants. *This work by Jimmy Smith is licensed under CC BY-NC-ND 4.0.*

Pest Control is a Common Tool

The management of pests is an essential part of agriculture, public health, and maintenance of power lines and roads. Chemical pest management has helped to reduce losses in agriculture and to limit human exposure to disease vectors, such as mosquitoes, saving many lives. Chemical pesticides can be effective, fast acting, adaptable to all crops and situations. When first applied, pesticides can result in impressive production gains of crops. However, despite these initial gains, excessive use of pesticides can be ecologically unsound, leading to the destruction of natural enemies, the increase of pesticide resistance, and outbreaks of secondary pests.

These consequences have often resulted in higher production costs as well as environmental and human health costs– side-effects which have been unevenly distributed. Despite the fact that the lion's share of chemical pesticides are applied in developed countries, 99 percent of all pesticide poisoning cases occur in developing countries where regulatory, health and education systems are weakest. Many farmers in developing countries overuse pesticides and do not take proper safety precautions because they do not understand the risks and fear smaller harvests. Making matters worse, developing countries seldom have strong regulatory systems for dangerous chemicals; pesticides banned or restricted in industrialized countries are used widely in developing countries. Farmers' perceptions of appropriate pesticide use vary by setting and culture. Prolonged exposure to pesticides has been associated with several chronic and acute health effects like non-Hodgkin's lymphoma, leukemia, as well as cardiopulmonary disorders, neurological and hematological symptoms, and skin diseases.

HUMAN HEALTH, ENVIRONMENTAL, AND ECONOMIC EFFECTS OF PESTICIDE USE IN POTATO PRODUCTION IN ECUADOR

The International Potato Center (CIP) conducted an interdisciplinary and inter-institutional research intervention project dealing with pesticide impacts on agricultural production, human health, and the environment in Carchi, Ecuador. Carchi is the most important potato-growing area in Ecuador, where smallholder farmers dominate production. They use tremendous amounts of pesticides for the control of the Andean potato weevil and the late blight fungus. Virtually all farmers apply class 1b highly toxic pesticides using hand pump backpack sprayers.

The study found that the health problems caused by pesticides are severe and are affecting a high percentage of the rural population. Despite the existence of technology and policy solutions, government policies continue to promote the use of pesticides. The study conclusions concurred with those by the pesticide industry, "that any company that could not ensure the safe use of highly toxic pesticides should remove them from the market and that it is almost impossible to achieve safe use of highly toxic pesticides among small farmers in developing countries."

Source: Yanggen et al. 2003.

Persistent Organic Pollutants

Persistent organic pollutants (POPs) are a group of organic chemicals, such as DDT, that have been widely used as pesticides or industrial chemicals and pose risks to human health and ecosystems. POPs have been produced and released into the environment by human activity. They have the following three characteristics:

- **Persistent**: POPs are chemicals that last a long time in the environment. Some may resist breakdown for years and even decades while others could potentially break down into other toxic substances.
- **Bioaccumulative**: POPs can accumulate in animals and humans, usually in fatty tissues and largely from the food they consume. As these compounds move up the food chain, they concentrate to levels that could be thousands of times higher than acceptable limits.
- **Toxic**: POPs can cause a wide range of health effects in humans, wildlife and fish. They have been linked to effects on the nervous system, reproductive and developmental problems, suppression of the immune system, cancer, and endocrine disruption. The deliberate production and use of most POPs has been banned around the world, with some exemptions made for human health considerations (e.g., DDT for malaria control) and/or in very specific cases where alternative chemicals have not been identified. However, the unintended production and/or the current use of some POPs continue to be an issue of global concern. Even though most POPs have not been manufactured or used for decades, they continue to be present in the environment and thus potentially harmful. The same properties that originally made them so effective, particularly their stability, make them difficult to eradicate from the environment.

POPs and Health

The relationship between exposure to environmental contaminants such as POPs and human health is complex. There is mounting evidence that these persistent, bioaccumulative and toxic chemicals (PBTs) cause long-term harm to human health and the environment. Drawing a direct link, however, between exposure to these chemicals and health effects is complicated, particularly since humans are exposed on a daily basis to many different environmental contaminants through the air they breathe, the water they drink, and the food they eat. Numerous studies link POPs with a number of adverse effects in humans. These include effects on the nervous system, problems related to reproduction and development, cancer, and genetic impacts. Moreover, there is mounting public concern over the environmental contaminants that mimic hormones in the human body (**endocrine disruptors**).

As with humans, animals are exposed to POPs in the environment through air, water and food. POPs can remain in sediments for years, where bottom-dwelling creatures consume them and who are then eaten by larger fish. Because tissue concentrations can increase or biomagnify at each level of the food chain, top predators (like largemouth bass or walleye) may have a million times greater concentrations of POPs than the water itself. The animals most exposed to PBT contaminants are those higher up the food web such as marine mammals including whales, seals, polar bears, and birds of prey in addition to fish species such as tuna, swordfish and bass (Figure 7.9.2). Once POPs are released into the environment, they may be transported within a specific region and across international boundaries transferring among air, water, and land.

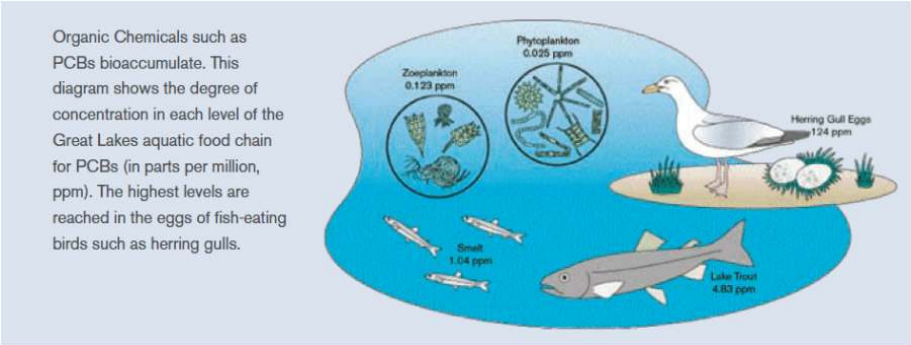


Figure 7.9.2. Bioaccumulation and biomagnification. U.S. EPA. Great Lakes: The Great Lakes Atlas: Chapter Four the Great Lakes Today – Concerns. January 2009

"Grasshopper Effect"

While generally banned or restricted, POPs make their way into and throughout the environment on a daily basis through a cycle of long-range air transport and deposition called the "**grasshopper effect.**"The "grasshopper" processes, illustrated in Figure 7.9.3,

begin with the release of POPs into the environment. When POPs enter the atmosphere, they can be carried with wind currents, sometimes for long distances.

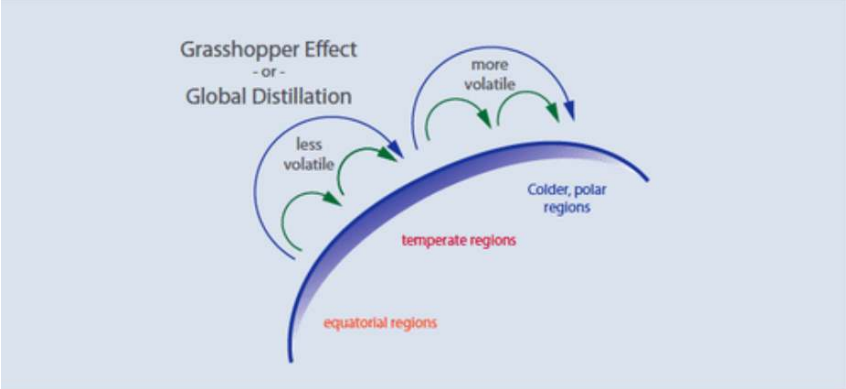


Figure 7.9.3. How POPs move throughout the environment. Source: Environment Canada. The Science and the Environment Bulletin. May/June 1998

Through atmospheric processes, they are deposited onto land or into water ecosystems where they accumulate and potentially cause damage. From these ecosystems, they evaporate, again entering the atmosphere, typically traveling from warmer temperatures toward cooler regions. They condense out of the atmosphere whenever the temperature drops, eventually reaching highest concentrations in circumpolar countries. Through these processes, POPs can move thousands of kilometers from their original source of release in a cycle that may last decades.

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7.10: Biotechnology and Genetic Engineering

In the early 1990s, an emerging disease was destroying Hawaii's production of papaya and threatening to decimate the $11 million industry (Figure 7.10.1). Fortunately, a man named Dennis Gonsalves, who was raised on a sugar plantation and then became a plant physiologist at Cornell University, would develop papaya plants genetically engineered to resist the deadly virus. By the end of the decade, the Hawaiian papaya industry and the livelihoods of many farmers were saved thanks to the free distribution of Dr. Gonsalves seeds.

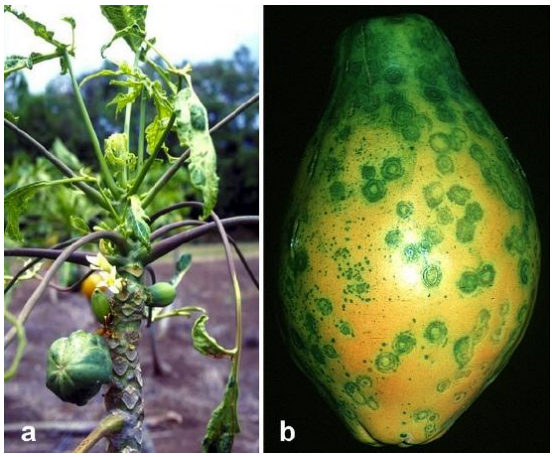


Figure 7.10.1. The symptoms of papaya ringspot virus are shown on the tree (a) and fruit (b). *"This work" is in the Public Domain, CC0.*

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

The History of Genetic Modification of Crops

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

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

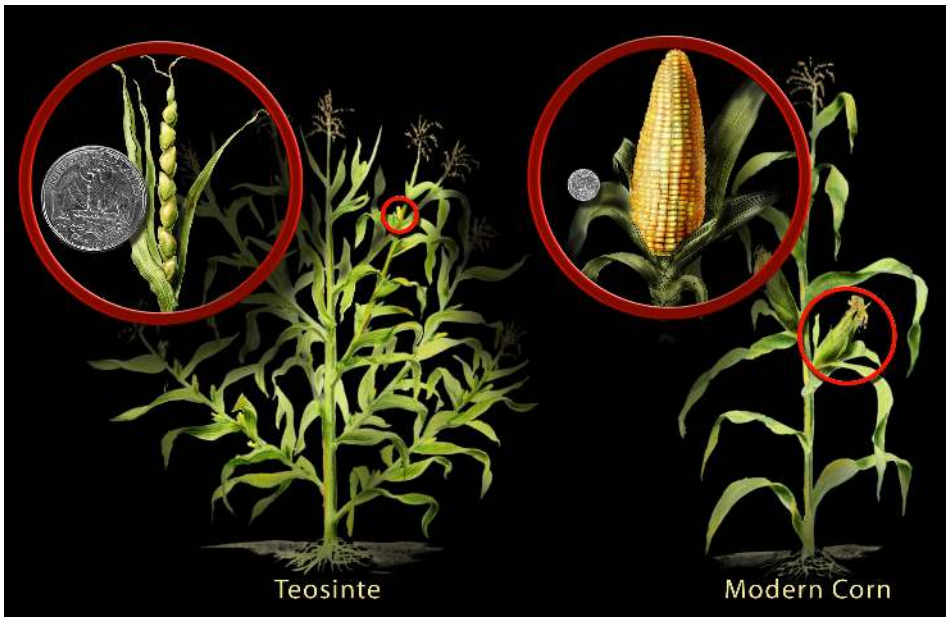


Figure 7.10.2. A wild grass called teosinte was genetically modified through selective breeding to produce what is now known as maize (corn). This process of transformation started thousands of years ago by indigenous people of what is now Mexico. *"This work" by Nicolle Rager Fuller, National Science Foundation is in the Public Domain, CC0.*

This history of genetic modification is common to nearly all crop species. For example, cabbage, broccoli, Brussel sprouts, cauliflower, and kale were all developed from a single species of wild mustard plant (Figure 7.10.2). Wild nightshade was the source of tomatoes, eggplant, tobacco, and potatoes, the latter developed by humans 7,000 – 10,000 years ago in South America.

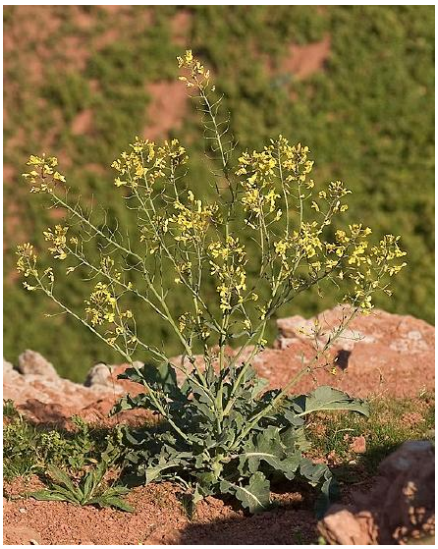


Figure 7.10.3. Brassica oleracea is a plant in the mustard family and is known as wild cabbage. From it were developed many familar crops, such as cauliflower, broccoli, Brussel sprouts, and of course, cabbage.*"Brassica oleracea wild" by Kulac is licensed under CC BY-SA 4.0*

Traditional Breeding v. Modern Genetic Engineering

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

How do traditional breeding practices compare to modern genetic engineering? Both result in changes to an organism's genetic information, but the magnitude of those changes varies amongst the two techniques (Figure 7.10.3). Traditional breeding shuffles all

of the genes between the two organisms being bred, which can number into the tens of thousands (maize, for example, has 32,000 genes). When mixing such a large number of genes, the results can be unpredictable. Modern genetic engineering is more precise in the sense that biologists can modify just a single gene. Also, genetic engineering can introduce a gene between two distantly-related species, such as inserting a bacterial gene into a plant. Such transfer might seem unusual, but it is not without its equivalent in nature. In a process called **horizontal gene transfer**, DNA from one species can be inserted into a different species. One recent study, for example, has found that humans contain about 150 genes from other species, including bacteria.

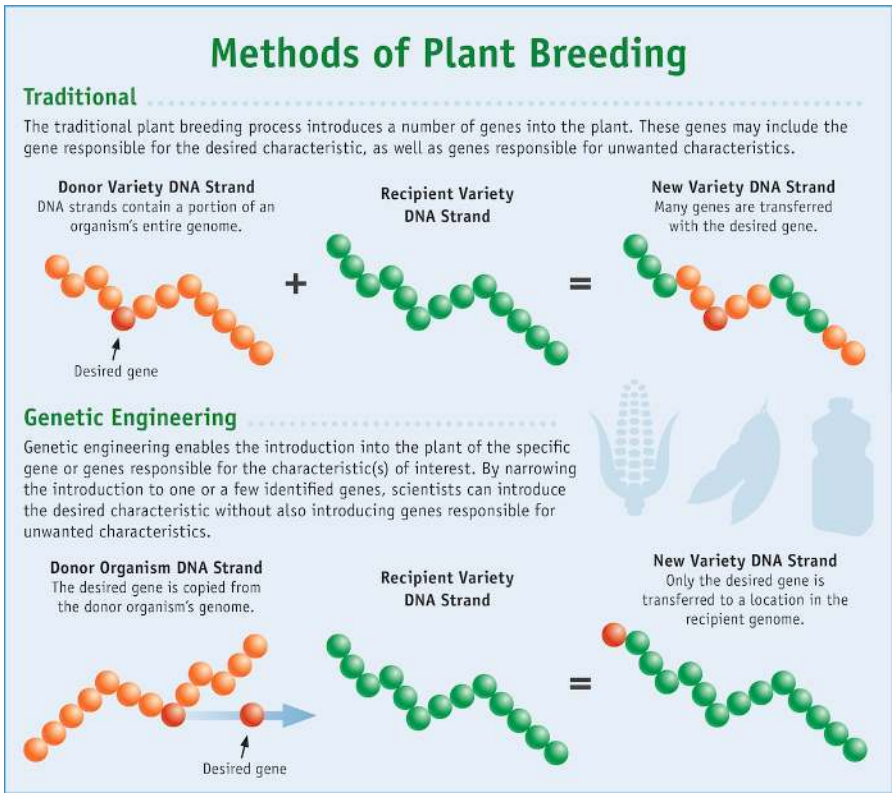


Figure 7.10.4. Both traditional breeding and modern genetic engineering produce genetic modifications. Genetic engineering allows for fewer and more precise genetic modifications. FDA graphic by Michael J. Ermarth (Methods of Plant Breeding) [CC0 Public Domain], via Wikimedia Commons.

Potential Benefits of Genetic Engineering

Enhanced nutrition

Advances in biotechnology may provide consumers with foods that are nutritionally-enriched (Figure 7.10.4), longer-lasting, or that contain lower levels of certain naturally occurring toxins present in some food plants. For example, developers are using biotechnology to try to reduce saturated fats in cooking oils, reduce allergens in foods, and increase disease-fighting nutrients in foods. Biotechnology may also be used to conserve natural resources, enable animals to more effectively use nutrients present in feed, decrease nutrient runoff into rivers and bays, and help meet the increasing world food and land demands.



Figure 7.10.5. White rice and Golden rice. Genetically engineered “Golden Rice” contains up to 35 µg β-carotene per gram of rice, which could prevent millions of cases of blindness worldwide.

Cheaper and More Manageable Production

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

Improved pest control

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



Figure 7.10.6. Worldwide, GE crops account for 12% of all agricultural production in 2015. Shown here are GE crops by nation. *“This work” by NASEM is in the Public Domain, CC0.*

Potential Concerns about Genetically Engineered Crops

The complexity of ecological systems presents considerable challenges for experiments that assess the risks and benefits of GE crops. Assessing such risks is difficult, because both natural and human-modified systems are highly complex and fraught with

uncertainties that may not be clarified until long after an experimental introduction has been concluded. Critics of GE crops warn that their cultivation should be carefully considered within broader ecosystems because of their potential benefits and hazards to the environment.

In addition to environmental risks, some people are concerned about potential health risks of GE crops because they feel that genetic modification alters the intrinsic properties, or essence, of an organism. As discussed above, however, it is known that both traditional breeding practices and modern genetic engineering produce permanent genetic modifications. Further, traditional breeding practices actually have a larger and more unpredictable impact on a species' genetics because of its comparably crude nature. Considering this, it is wise that both new GE crops and traditionally produced crops should be studied for potential human health risks.

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

Interbreeding with Native Species

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

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

Consumers Right to Choose

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

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

Long-Term Ecological Effects

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

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

The GE Crop Report also mentioned a separate threat to monarch: loss of milkweed, which is critical to the butterfly's lifecycle. Some GE crops are engineered to resist the herbicide glyphosate. Farmers using these crops can spray their entire field with the herbicide, which kills milkweed but not their GE crop. This can lower the amount of milkweed growing within the habitat range of

monarchs. The report concluded that more studies are needed to quantify the actual impact this may be having on monarch populations.

Human Health Risk

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

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

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

Intellectual Property Rights

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

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

Are GE Crops the Solution We Need?

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

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

Genetic engineering of crops represents in important tool in a world of rapidly changing climate and a burgeoning human population, but as you will see in the next chapter, it is only one of many tools that agriculturists can use to produce enough food

for all humans while simultaneously working to conserve the environment.

Suggested Supplementary Reading:

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

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

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CHAPTER OVERVIEW

8: Environmental Health and Toxicology

8.1: The Impacts of Environmental Conditions
8.2: Environmental Health
8.3: Environmental Toxicology
8.4: Bioremediation
8.5: Biological Magnification
8.6: Risk Assessment and Management
8.7: Case Study - The Love Canal Disaster

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8.1: The Impacts of Environmental Conditions

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

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

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



Figure 8.1.1. DDT was a commonly-used pesticide. *"This work" by OpenStax is licensed under CC BY 4.0.*

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

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8.2: Environmental Health

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

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

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

Poverty, Health and Environment

Environmental health risks can be grouped into two broad categories. **Traditional hazards** are related to poverty and the lack of development and mostly affect developing countries and poor people. Their impact exceeds that of modern health hazards by 10 times in Africa, 5 times in Asian countries (except for China), and 2.5 times in Latin America and Middle East (Figure 8.2.1). Water-related diseases caused by inadequate water supply and sanitation impose an especially large health burden in Africa, Asia, and the Pacific region. In India alone, over 700,000 children under 5 die annually from diarrhea. In Africa, malaria causes about 500,000 deaths annually. More than half of the world's households use unprocessed *solid fuels*, particularly biomass (crop residues, wood, and dung) for cooking and heating in inefficient stoves without proper ventilation, exposing people—mainly poor women and children—to high levels of indoor air pollution(IAP). IAP causes about 2 million deaths in each year.

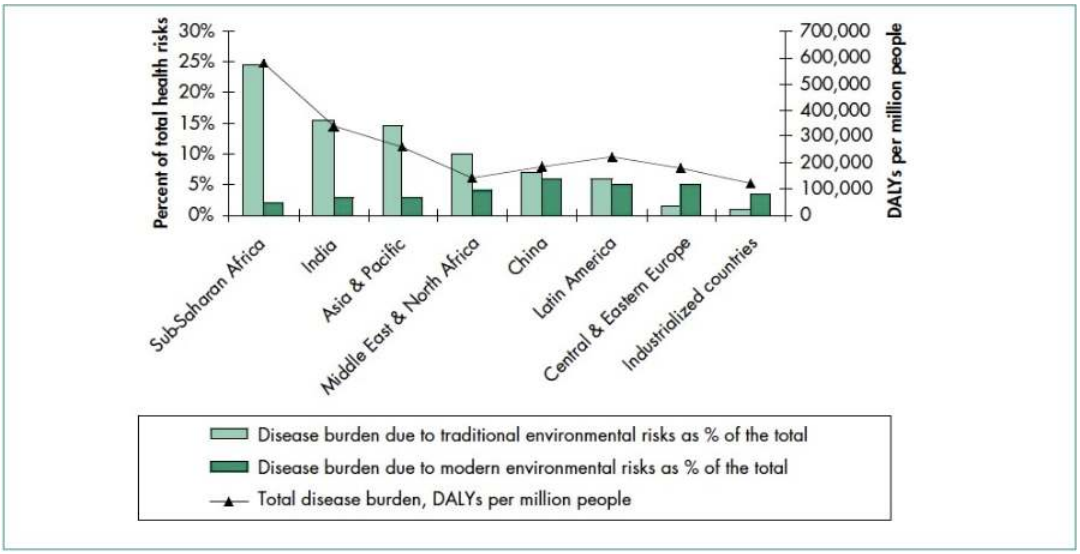


Figure 8.2.1. Traditional environmental health hazards prevail in developing countries but modern risks are also significant.

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

Environmental Health and Child Survival



Figure 8.2.2. Malnourished children in Niger, during the 2005 famine.

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

Poor Water and Sanitation Access

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

Indoor Air Pollution

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

Malaria

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

Emerging Diseases

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

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

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

The **HIV/AIDS** epidemic has spread with ferocious speed. Virtually unknown 20 years ago, HIV has infected more than 60 million people worldwide. Each day, approximately 14,000 new infections occur, more than half of them among young people below age 25. Over 95 percent of PLWHA (People Living With HIV/AIDS) are in low- and middle- income countries. More than 20 million have died from AIDS, over 3 million in 2002 alone. AIDS is now the leading cause of death in Sub-Saharan Africa and the fourth-biggest killer globally. The epidemic has cut life expectancy by more than 10 years in several nations.

It seems likely that a wide variety of infectious diseases have affected human populations for thousands of years emerging when the environmental, host, and agent conditions were favorable. Expanding human populations have increased the potential for transmission of infectious disease as a result of close human proximity and increased likelihood for humans to be in "the wrong place at the right time" for disease to occur (eg, natural disasters or political conflicts). Global travel increases the potential for a

carrier of disease to transmit infection thousands of miles away in just a few hours, as evidenced by WHO precautions concerning international travel and health.

Antibiotic Resistance

Antibiotics and similar drugs, together called antimicrobial agents, have been used for the last 70 years to treat patients who have infectious diseases. Since the 1940s, these drugs have greatly reduced illness and death from infectious diseases. However, these drugs have been used so widely and for so long that the infectious organisms the antibiotics are designed to kill have adapted to them, making the drugs less effective. **Antibiotic resistance** occurs when bacteria change in a way that reduces the effectiveness of drugs, chemicals, or other agents designed to cure or prevent infections. This is caused by the process of evolution through natural selection (Figure 8.2.3). The antibiotic-resistant bacteria survive and continue to multiply, causing more harm.

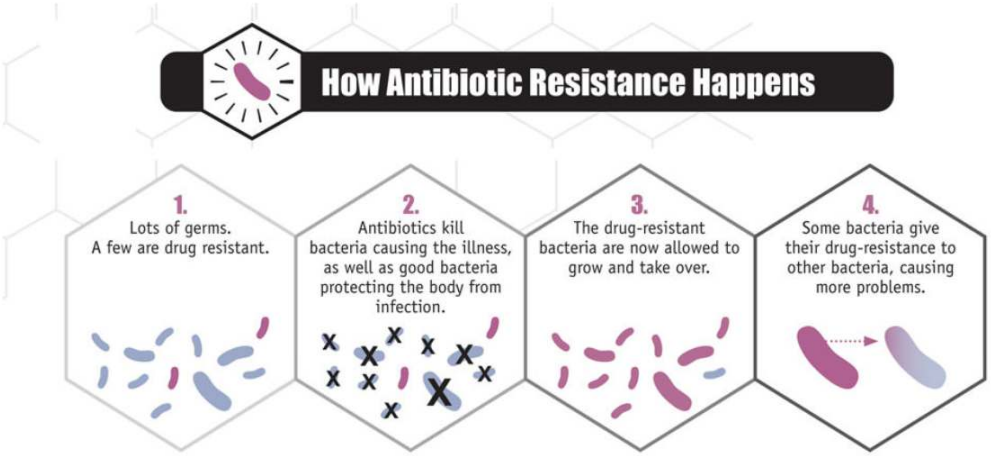


Figure 8.2.3. Antibiotic resistance is of increasing concern to medical professionals.

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



Video 8.2.1. Click here for a video link to an experiment done at Harvard Medical school, where they show bacteria adapting very quickly to apparently deadly conditions.

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

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

The "Dirty Dozen" and "Clean Fifteen" are lists published annually by the Environmental Working Group (EWG) to inform consumers about pesticide residues on conventionally grown fruits and vegetables. These lists aim to guide shoppers on which produce items to prioritize buying organic to potentially reduce exposure to pesticides.

The Dirty Dozen- This list comprises the 12 fruits and vegetables most likely to have high pesticide residue levels, even after washing and peeling. The EWG suggests opting for organic versions of these foods when possible



From “Day 5 Clean Cleanse” by Shelly In Real Life, CC BY-NC-ND 2.0

The Clean Fifteen- This list features fruits and vegetables with the lowest pesticide residues, making them safer choices if organic isn't an option. Many of these items have tough outer peels that are typically removed before eating. Almost 60% of samples for all Clean Fifteen fruits and vegetables had no detectable pesticide residues.

- Pineapple
- Sweet Corn (fresh and frozen)
- Avocados
- Papaya
- Onions
- Sweet Peas (frozen)
- Asparagus
- Cabbage
- Watermelon
- Cauliflower
- Bananas
- Mangoes
- Carrots
- Mushrooms
- Kiwi

Suggested Supplementary Reading:

EWG’s Shopper’s Guide to Pesticides in Produce

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

> *Notable Excerpts:*
>
> *"Antibiotic use in food animals is correlated with antibiotic resistance among bacteria affecting human populations." p. 311*
>
> *"Microbial genes encoding antibiotic resistance have moved between the food-animal and human health sectors, resulting in illnesses that could not be treated by antibiotics." p. 312*

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8.3: Environmental Toxicology

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

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

Routes of Exposure to Chemicals

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

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

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

What Forms do Chemicals Take?

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

What Health Effects Can Chemicals Cause?

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

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

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

Environmental Contaminants

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

Table 2. Classification of Environmental Contaminants

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

An Overview of Some Common Contaminants

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

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

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

Although fish and shellfish have many nutritional benefits, consuming large quantities of fish increases a person's exposure to mercury. Pregnant women who eat fish high in mercury on a regular basis run the risk of permanently damaging their developing fetuses. Children born to these mothers may exhibit motor difficulties, sensory problems and cognitive deficits. Figure 8.3.1 identifies the typical (average) amounts of mercury in commonly consumed commercial and sport-caught fish.

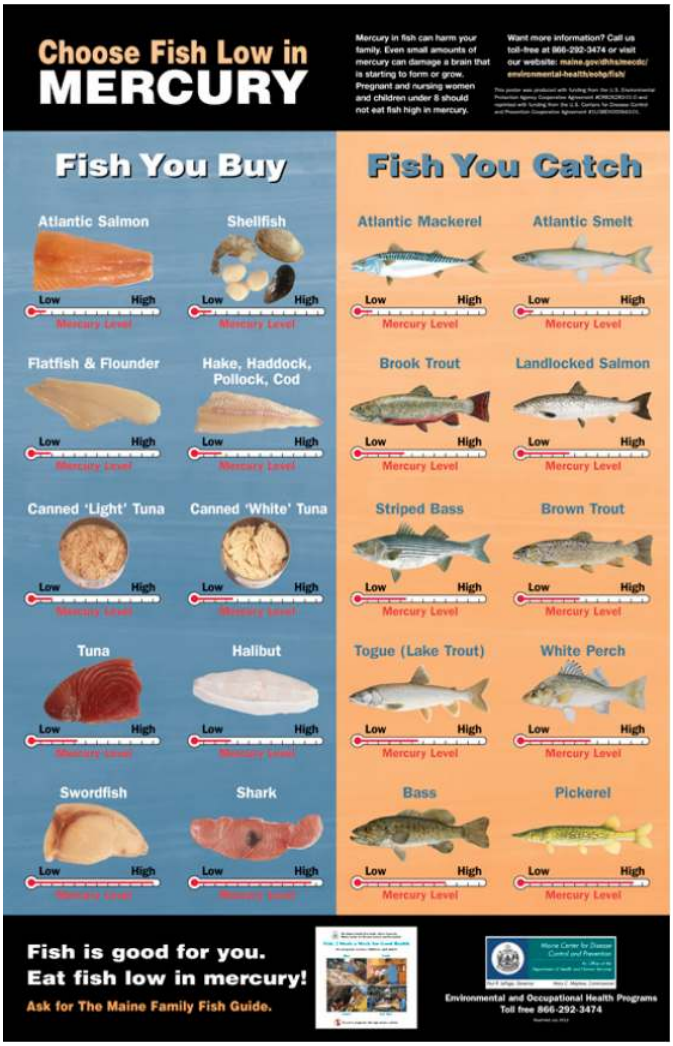


Figure 8.3.1. Mercury concentrations in fish can reach potentially dangerous levels (published by the *Maine Center for Disease Control & Prevention*).

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

What can I do to prevent exposure to BPA?

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

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

- Use baby bottles that are BPA free.

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

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

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



Figure 8.3.2. Nail products are known to contain toxic chemicals, such as dibutyl phthalate (DBP), toluene, and formaldehyde.

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

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

Radiation

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

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

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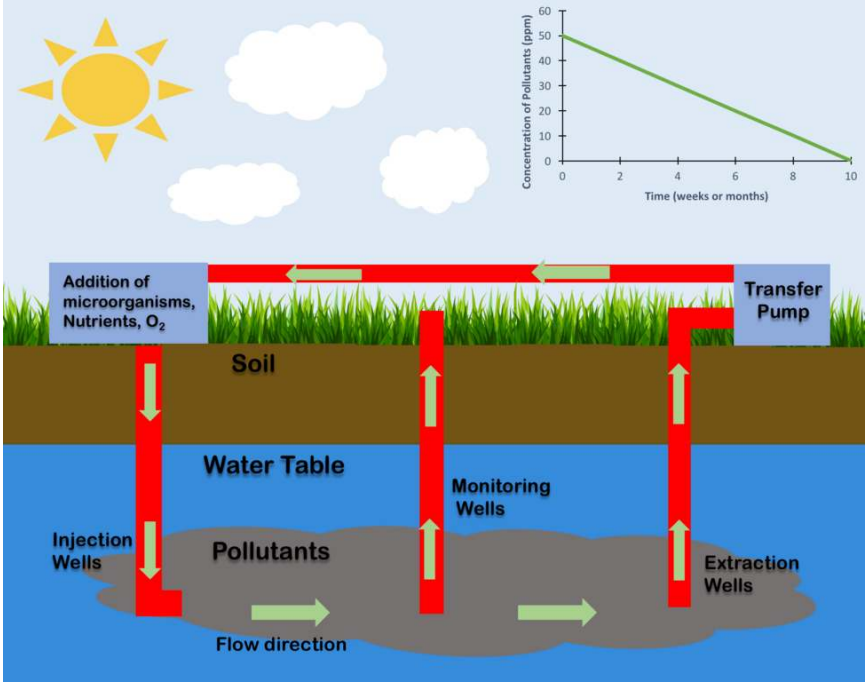
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8.4: Bioremediation

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



Bioremediation. Hoodlind, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

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

Probably one of the most useful and interesting examples of the use of prokaryotes for bioremediation purposes is the cleanup of oil spills. The importance of prokaryotes to petroleum bioremediation has been demonstrated in several oil spills in recent years, such as the Exxon Valdez spill in Alaska (1989) (Figure 8.4.1), the Prestige oil spill in Spain (2002), the spill into the Mediterranean from a Lebanon power plant (2006,) and more recently, the BP oil spill in the Gulf of Mexico (2010). To clean up these spills, bioremediation is promoted by adding inorganic nutrients that help bacteria already present in the environment to grow. Hydrocarbon-degrading bacteria feed on the hydrocarbons in the oil droplet, breaking them into inorganic compounds. Some species, such as *Alcanivorax borkumensis*, produce surfactants that solubilize the oil, while other bacteria degrade the oil into carbon dioxide. In the case of oil spills in the ocean, ongoing, natural bioremediation tends to occur, inasmuch as there are oil-consuming bacteria in the ocean prior to the spill. Under ideal conditions, it has been reported that up to 80 percent of the nonvolatile components in oil can be degraded within 1 year of the spill. Researchers have genetically engineered other bacteria to consume petroleum products; indeed, the first patent application for a bioremediation application in the U.S. was for a genetically modified oil-eating bacterium.



(a) (b)

Figure 8.4.1. (a) Cleaning up oil after the Valdez spill in Alaska, the workers hosed oil from beaches and then used a floating boom to corral the oil, which was finally skimmed from the water surface. Some species of bacteria are able to solubilize and degrade the oil. (b) One of the most catastrophic consequences of oil spills is the damage to fauna. (credit a: modification of work by NOAA; credit b: modification of work by GOLUBENKOV, NGO: Saving Taman)

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

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8.5: Biological Magnification

Learning Objectives

- Describe the consequences of biomagnification between trophic levels

Consequences of Food Webs: Biological Magnification

One of the most important environmental consequences of ecosystem dynamics is biomagnification: the increasing concentration of persistent, toxic substances in organisms at each trophic level, from the primary producers to the apex consumers. Many substances have been shown to bioaccumulate, including classical studies with the pesticide dichlorodiphenyltrichloroethane (DDT), which was published in the 1960s bestseller, *Silent Spring*, by Rachel Carson. DDT was a commonly-used pesticide before its dangers became known. In some aquatic ecosystems, organisms from each trophic level consumed many organisms of the lower level, which caused DDT to increase in birds (apex consumers) that ate fish. Thus, the birds accumulated sufficient amounts of DDT to cause fragility in their eggshells. This effect increased egg breakage during nesting, which was shown to have adverse effects on these bird populations. The use of DDT was banned in the United States in the 1970s.

Other substances that biomagnify are polychlorinated biphenyls (PCBs), which were used in coolant liquids in the United States until their use was banned in 1979, and heavy metals, such as mercury, lead, and cadmium. These substances were best studied in aquatic ecosystems where fish species at different trophic levels accumulate toxic substances brought through the ecosystem by the primary producers. In a study performed by the National Oceanic and Atmospheric Administration (NOAA) in the Saginaw Bay of Lake Huron, PCB concentrations increased from the ecosystem's primary producers (phytoplankton) through the different trophic levels of fish species. The apex consumer (walleye) had more than four times the amount of PCBs compared to phytoplankton. Also, based on results from other studies, birds that eat these fish may have PCB levels at least one order of magnitude higher than those found in the lake fish.

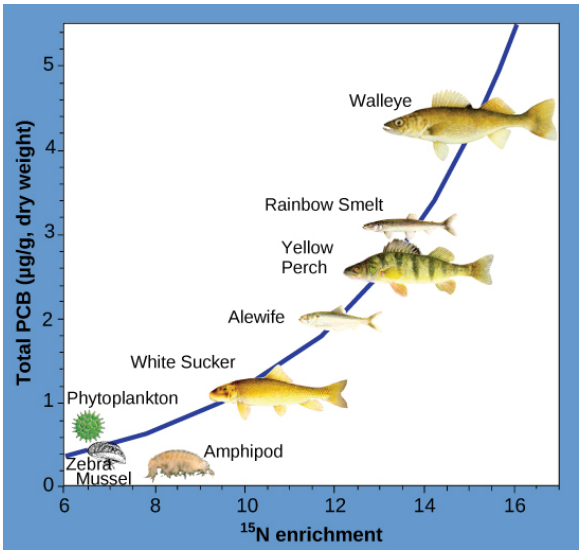
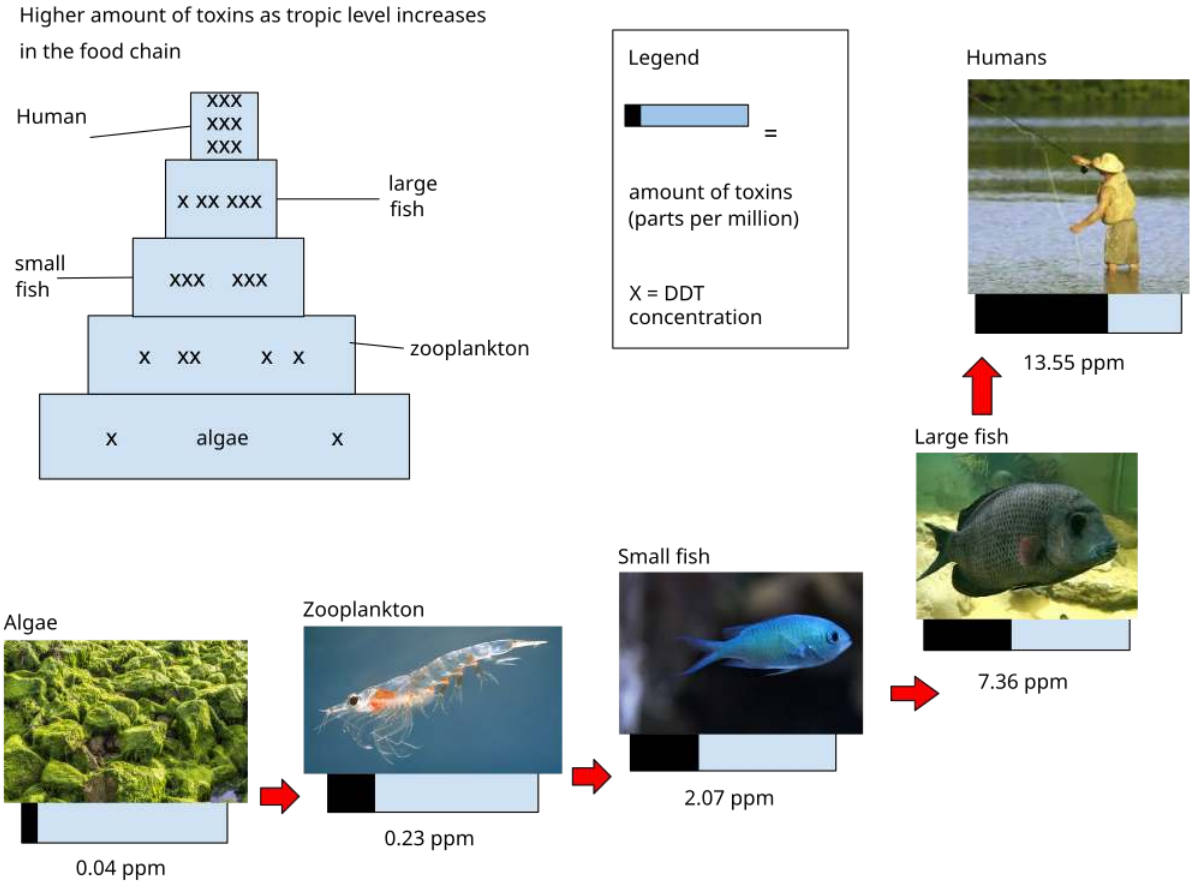


Figure 8.5.1: PCB concentration in Lake Huron: This chart shows the PCB concentrations found at the various trophic levels in the Saginaw Bay ecosystem of Lake Huron. Numbers on the x-axis reflect enrichment with heavy isotopes of nitrogen (15N), which is a marker for increasing trophic levels. Notice that the fish in the higher trophic levels accumulate more PCBs than those in lower trophic levels.

Other concerns have been raised by the accumulation of heavy metals, such as mercury and cadmium, in certain types of seafood. The United States Environmental Protection Agency (EPA) 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, sardines, tilapia, shrimp, pollock, and catfish. Biomagnification is a good example of how ecosystem dynamics can affect our everyday lives, even influencing the food we eat.



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Key Points

- Biomagnification increases the concentration of toxic substances in organisms at higher trophic levels.
- DDT is an example of a substance that biomagnifies; birds accumulate sufficient amounts of DDT from eating fish to cause adverse effects on bird populations.
- The presence of polychlorinated biphenyls (PCB) in phytoplankton causes increased PCB concentrations in walleyes and birds.
- Heavy metals, such as mercury and cadmium, found in certain types of seafood can also biomagnify.

Key Terms

- **biomagnification**: the process, in an ecosystem, in which a higher concentration of a substance in an organism is obtained higher up the food chain
- **dichlorodiphenyltrichloroethane**: a chlorinated hydrocarbon which is mainly used as an insecticide (DDT)
- **apex consumer**: consumers with few to no predators of their own, residing at the top of their food chain

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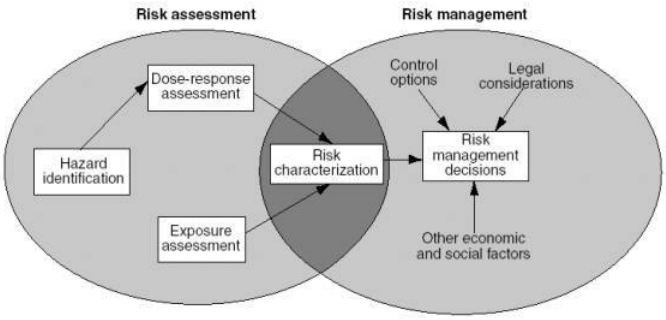
8.6: Risk Assessment and Management

Risk assessment is a scientific process used by federal agencies and risk management decision-makers to make informed decisions about actions that may be taken to protect human health by ascertaining potential human health risks or health hazard associated with exposure to chemicals in the environment. Some of the real-world examples of risk assessment includes: establishment of national ambient air quality and drinking water standards for protection of public health (e.g. ozone, particulate matter in outdoor air; chromium, chloroform or benzene in water); establishment of clean-up levels for hazardous waste site remediation; development of fish consumption advisories for pregnant women and general population (e.g. PCBs, mercury); assessment of risks and benefits of different alternative fuels for sound energy policy development (e.g. oxygenated gasoline, biodiesel); and estimation of health risks associated with pesticide residues in food. The estimated risk is a function of exposure and toxicity. The regulatory risk assessment follows a four-step paradigm using qualitative and/or quantitative approaches. In quantitative risk assessment using either deterministic or probabilistic approaches, the risk estimates pertaining to an exposure scenario is particularly useful when comparing a number of exposure or risk reduction measures among one another as an optimization protocol to determine the best economically viable option for protection of public health and the environment. The four steps of risk assessment are i) hazard identification; ii) toxicity (or dose-response) assessment; iii) exposure assessment; and iv) risk characterization, which are described below in detail. The emphasis is given in documenting the resources necessary to successfully perform each step.

1. In the hazard identification step, a scientific weight of evidence analysis is performed to determine whether a particular substance or chemical is or is not causally linked to any particular health effect at environmentally relevant concentrations. Hazard identification is performed to determine whether, and to what degree, toxic effects in one setting will occur in other settings. The evidence comes from human but also animal studies.
2. Toxicity or dose-response assessment takes the toxicity data gathered in the hazard identification step from animal studies and exposed human population studies and describes the quantitative relationship between the amount of exposure to a chemical (or dose) and the extent of toxic injury or disease (or response). Generally, as the dose of a chemical increases, the toxic response increases either in the severity of the injury or in the incidence of response in the affected population.
3. The magnitude of exposure is determined by measuring or estimating the amount of an agent to which humans are exposed (i.e. exposure concentration) and the magnitude of dose (or intake) is estimated by taking the magnitude, frequency, duration, and route of exposure into account. Exposure assessments may consider past, present, and future exposures.
4. In the last step, a hazard quotient (HQ) as an indicator of risks associated with health effects other than cancer and excess cancer risk as the incremental probability of an exposed person developing cancer over a lifetime, are calculated by integrating toxicity and exposure information.

The improvement in the scientific quality and validity of health risk estimates depends on advancements in our understanding of human exposure to, and toxic effects associated with, chemicals present in environmental and occupational settings. Risk assessments are important for informed regulatory decision-making in environmental sustainability and to ensure that costs associated with different technological alternatives are scientifically justified and protest public health. Risk assessment helps federal agencies and risk management decision makers arrive at informed decisions about actions to take to protect human health from environmental hazards. Although significant uncertainties remain, this risk assessment methodology has been extensively peer-reviewed, is widely used and understood by the scientific community, and continues to expand and evolve as scientific knowledge advances.

Risk management (Figure below) is distinct from risk assessment, and involves the integration of risk assessment with other considerations, such as economic, social, or legal concerns, to reach regulatory decisions regarding the need for and practicability of implementing various risk reduction activities.



Source: EPA Office of Research and Development.

Figure 8.6.1: Risk Assessment and Management

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?

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8.7: Case Study - The Love Canal Disaster

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



Figure 8.7.1. Love Canal. Source: US Environmental Protection Agency

Love Canal is a neighborhood in Niagara Falls named after a large ditch (approximately 15 m wide, 3–12 m deep, and 1600 m long) that was dug in the 1890s for hydroelectric power. The ditch was abandoned before it actually generated any power and went mostly unused for decades, except for swimming by local residents. In the 1920s Niagara Falls began dumping urban waste into Love Canal, and in the 1940s the U.S. Army dumped waste from World War II there, including waste from the frantic effort to build a nuclear bomb. Hooker Chemical purchased the land in 1942 and lined it with clay. Then, the company put into Love Canal an estimated 21,000 tons of hazardous chemical waste, including the carcinogens benzene, dioxin, and PCBs in large metal barrels and covered them with more clay. In 1953, Hooker sold the land to the Niagara Falls school board for $1, and included a clause in the sales contract that both described the land use (filled with chemical waste) and absolved them from any future damage claims from the buried waste. The school board promptly built a public school on the site and sold the surrounding land for a housing project that built 200 or so homes along the canal banks and another 1,000 in the neighborhood (Figure 8.7.1). During construction, the canal's clay cap and walls were breached, damaging some of the metal barrels.

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

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

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CHAPTER OVERVIEW

9: Climate

9.1: Climate and Weather
9.2: Atmosphere and Climate Regulation
9.3: Milankovitch Cycles and the Climate of the Quaternary
9.4: Causes of Global Climate Change
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9.6: Past and Present Effects of Climate Change
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9.1: Climate and Weather

Learning Objectives

- Distinguish between climate and weather

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) is 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 temperature and annual 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; while long-range weather forecasts are available, they can be unreliable.

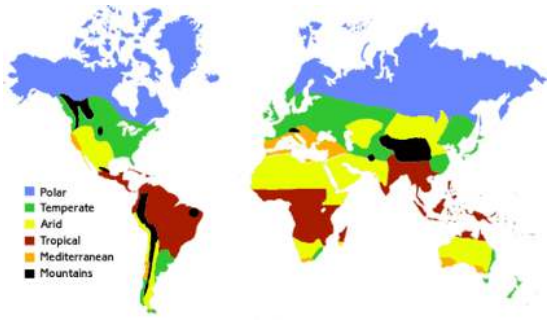


Figure 9.1.1: Climate: Climate refers to long-term, predictable atmospheric conditions of a specific area. Weather, in contrast, refers to the conditions of the atmosphere during a short period of time. This map illustrates the various climate conditions around the world.

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 because it is difficult to accurately predict the weather on a specific day. Climate can be considered “average” weather.

Key Points

- Climate refers to the long-term, predictable atmospheric conditions of a specific area; it does not address the amount of rain that fell on one particular day or the colder-than-average temperatures on a given day in a biome.
- Weather refers to the conditions of the atmosphere during a short period of time; weather forecasts are usually made for 48-hour cycles.
- Specific, one-off weather occurrences are not necessarily indicators of climate change.

Key Terms

- **biome**: any major regional biological community such as that of forest or desert
- **climate**: long-term manifestations of weather and other atmospheric conditions in a given area or country in a period long enough to ensure that representative values are obtained (generally 30 years)
- **weather**: the short term state of the atmosphere at a specific time and place, including the temperature, humidity, cloud cover, precipitation, wind, etc.

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9.2: Atmosphere and Climate Regulation

Life on earth plays a critical role in regulating the earth's physical, chemical, and geological properties, from influencing the chemical composition of the atmosphere to modifying climate.

About 3.5 billion years ago, early life forms (principally cyanobacteria) helped create an oxygenated atmosphere through photosynthesis, taking up carbon dioxide from the atmosphere and releasing oxygen (Schopf 1983; Van Valen 1971). Over time, these organisms altered the composition of the atmosphere, increasing oxygen levels, and paved the way for organisms that use oxygen as an energy source (aerobic respiration), forming an atmosphere similar to that existing today.

Carbon cycles on the planet between the land, atmosphere, and oceans through a combination of physical, chemical, geological, and biological processes (IPCC 2001). One key way biodiversity influences the composition of the earth's atmosphere is through its role in carbon cycling in the oceans, the largest reservoir for carbon on the planet (Gruber and Sarmiento, in press). In turn, the atmospheric composition of carbon influences climate. Phytoplankton (or microscopic marine plants) play a central role in regulating atmospheric chemistry by transforming carbon dioxide into organic matter during photosynthesis. This carbon-laden organic matter settles either directly or indirectly (after it has been consumed) in the deep ocean, where it stays for centuries, or even thousands of years, acting as the major reservoir for carbon on the planet. In addition, carbon also reaches the deep ocean through another biological process -- the formation of calcium carbonate, the primary component of the shells in two groups of marine organisms coccolithophorids (a phytoplankton) and foraminifera (a single celled, shelled organism that is abundant in many marine environments). When these organisms die, their shells sink to the bottom or dissolve in the water column. This movement of carbon through the oceans removes excess carbon from the atmosphere and regulates the earth's climate.

Over the last century, humans have changed the atmosphere's composition by releasing large amounts of carbon dioxide. This excess carbon dioxide, along with other 'greenhouse' gases, is believed to be heating up our atmosphere and changing the world's climate, leading to 'global warming'. There has been much debate about how natural processes, such as the cycling of carbon through phytoplankton in the oceans, will respond to these changes. Will phytoplankton productivity increase and thereby absorb the extra carbon from the atmosphere? Recent studies suggest that natural processes may slow the rate of increase of carbon dioxide in the atmosphere, but it is doubtful that either the earth's oceans or its forests can absorb the entirety of the extra carbon released by human activity (Falkowski et al. 2000).

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9.3: Milankovitch Cycles and the Climate of the Quaternary

Learning Objectives

After reading this module, students should be able to

- describe the changing climate of the Quaternary
- explain why Milankovitch cycles explain the variations of climate over the Quaternary, in terms of the similar periods of orbital variations and glacial cycles
- explain how the glacier/climate system is linked via albedo feedbacks
- describe how sediment and ice cores provide information about past climates
- use the mechanisms that cause stable isotope fractionation to predict the impact of changing climate on stable isotope records

Introduction

In Module 5.2 we saw the major drivers of the climate—the energy that comes from the Sun (insolation) and the properties of the planet that determine how long that energy stays in the Earth system (albedo, greenhouse gases). In this section, we will look at the recent natural changes in Earth's climate, and we will use these drivers to understand why the climate has changed.

The most recent period of Earth's geologic history—spanning the last 2.6 million years—is known as the quaternary period. This is an important period for us because it encompasses the entire period over which humans have existed—our species evolved about 200,000 years ago. We will examine how the climate has changed over this period in detail. By understanding recent natural processes of climate change, we will be able to better understand why scientists attribute the currently observed changes in global climate as being the result of human activity.

Quaternary Climate — Information From Ice Cores

How do we know about the Quaternary climate? After all, most of the period predates human existence, and we have only been recording the conditions of climate for a few centuries. Scientists are able to make informed judgments about the climates of the deep past by using proxy data. Proxy data is information about the climate that accumulates through natural phenomena. In the previous module, for example, we discussed how 60-million-year-old crocodile fossils have been found in North Dakota. This gives us indirect information about the climate of the period—that the climate of the region was warmer than it is today. Although not as precise as climate data recorded by instruments (such as thermometers), proxy data has been recovered from a diverse array of natural sources, and provides a surprisingly precise picture of climate change through deep time.

One highly detailed record of past climate conditions has been recovered from the great ice sheets of Greenland and Antarctica. These ice sheets are built by snow falling on the ice surface and being covered by subsequent snowfalls. The compressed snow is transformed into ice. It is so cold in these polar locations that the ice doesn't melt even in the summers, so the ice is able to build up over hundreds of thousands of years. Because the ice at lower depths was produced by progressively earlier snowfalls, the age of the ice increases with depth, and the youngest ice is at the surface. The Antarctic ice sheet is up to three miles thick. It takes a long time to build up this much ice, and the oldest ice found at the bottom of the Antarctica ice sheet is around 800,000 years old.

Scientists drill into these ice sheets to extract *ice cores*, which record information about past climates. Figure 9.3.1 shows what these cores look like when they are cut open. Like tree rings, ice cores indicate years of growth. Note how the middle core (which required over a mile of drilling to extract!) has distinct layers—this is because the seasons leave an imprint in the layers of snow. Scientists can use this imprint to help calculate the age of the ice at different depths, although the task becomes more difficult the deeper the core sample, since the ice layers become more compressed. The ice records several different types of climate information: the temperature of the core, the properties of the water that make up the ice, trapped dust, and tiny entombed bubbles of ancient atmosphere.

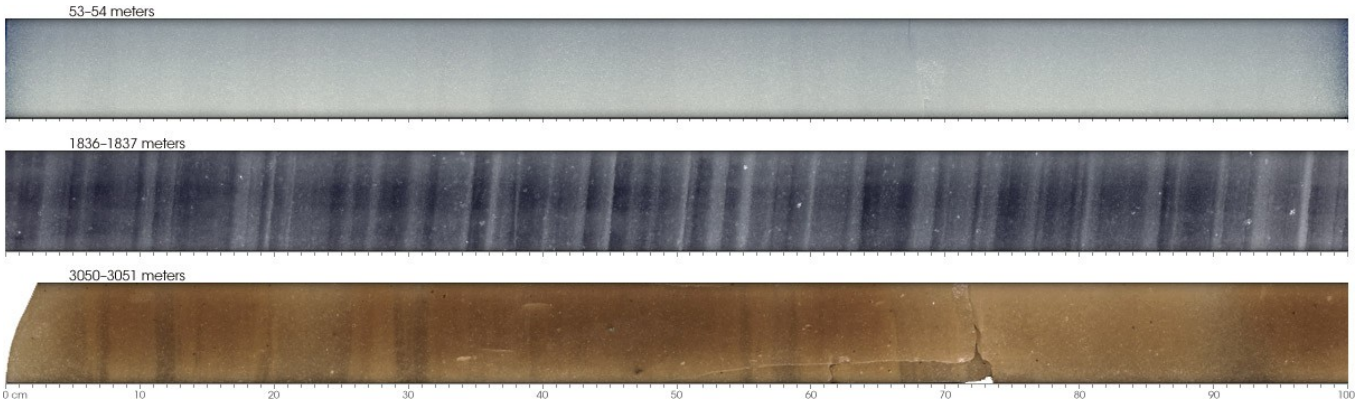


Figure 9.3.1 Ice cores. Three different sections of an ice core. The seasonal layers are most clear in the middle section (note the dark and light bands). The deepest section (bottom core) is taken from almost two miles down and is colored brown by rocky debris from the ground under the ice. *Source:* *National Ice Core Laboratory*

The water molecules that make up the ice record information about the temperature of the atmosphere. Each water molecule is made up of two hydrogen atoms and one oxygen atom (and so has the chemical name H_2O). Not all oxygen atoms are the same however; some are "light" and some are "heavy". These different types of oxygen are called isotopes, which are atoms that have same number of protons but different numbers of neutrons. The heavy isotope of oxygen (oxygen-18, or ^{18}O) is more than 10% heavier than the light isotope (oxygen-16 or ^{16}O). This means that some water molecules weigh more than others. This is important because lighter water molecules are more easily evaporated from the ocean, and once in the atmosphere, heavier water molecules are more likely to condense and fall as precipitation. As we can see from Figure 9.3.2, the water in the ice sheets is lighter (has a higher proportion of ^{16}O relative to ^{18}O) than the water in the oceans.

The process of differentiation between heavy and light water molecules is temperature dependent. If the atmosphere is warm, there is more energy available to evaporate and hold the heavier ^{18}O water in the atmosphere, so the snow that falls on the polar ice sheets is relatively higher in ^{18}O. When the atmosphere is cold, the amount of energy is less, and so less ^{18}O makes it to the poles to be turned into glacial ice. We can compare the amount of ^{18}O in different parts of the ice core to see how the atmosphere's temperature—the climate—has changed.

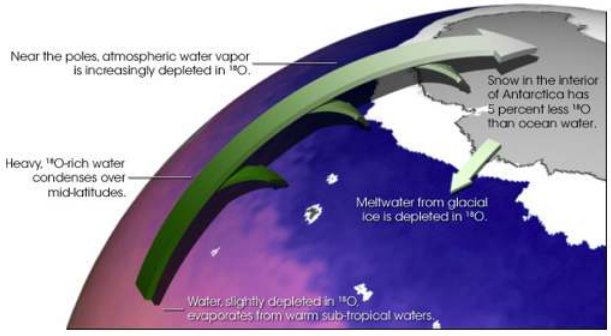


Figure 9.3.2 Water becomes lighter as it travels toward the poles. The heavy (18O) water drops out of the atmosphere (as rain or snow) before reaching the ice sheet. This means that the snow that forms the glacial ice is lighter than the ocean water (has more 16O than 18O, compared to ocean water). *Source:* *Robert Simmon, NASA GSFC, NASA Earth Observatory*

Figure 9.3.3 shows what this record looks like over the last 400,000 years. The blue and green lines depict two different Antarctic ice cores (taken from ice about 350 miles apart) and the variations in oxygen isotopes are converted into temperature changes. The y-axis shows temperature change; today's climate is at zero—the dashed line. Notice that the Earth's climate has not been stable! Sometimes the temperature is higher than it is today—the blue and green lines are higher than the dashed about 120,000 years ago, for example. Most of the time the climate is much colder than today's, however: the most common value is around -6 ^{o}C (-13 ^{o}F). On average, the earth's temperature between 25,000 and 100,000 years ago was about 6 ^{o}C lower than it is today. These changes

can be double-checked by measuring the temperature of the ice in the cores directly. Ice that is 30,000 years old is indeed colder than the ice made today, just as the isotope data predicts.

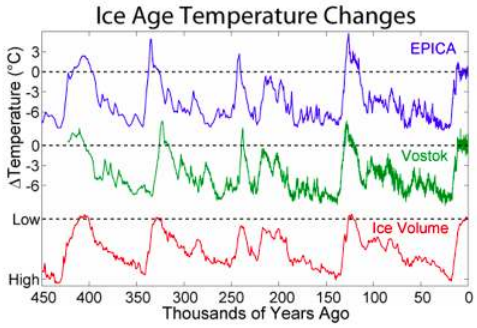


Figure 9.3.3 Ice age temperature. The blue and green lines depict two different Antarctic ice cores (taken from ice about 350 miles apart) and the variations in oxygen isotopes are converted into temperature changes. The red line depicts global ice volume. The y-axis shows temperature change; today's climate is at zero – the dashed line. *Source:* *Robert A. Rohde*

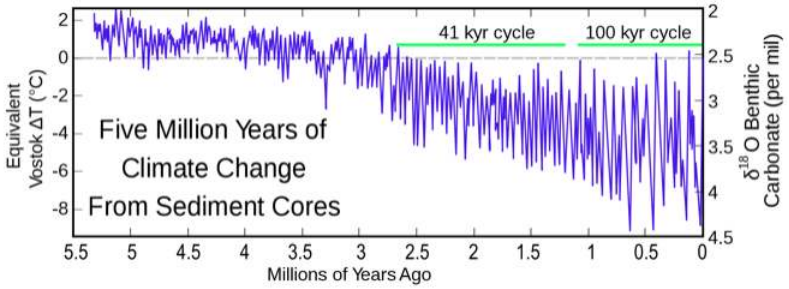


Figure 9.3.4 A comparison of the age of sediment (x-axis) and the change in temperature over time (left y-axis) as derived from oxygen isotope ratios (right y-axis). The dashed line shows today's climate. Note that the climate is cooling over the last few million years, but it is highly variable. In the last one million years the climate alternates between warm and cool conditions on a 100,000-year time scale ("100 kyr cycle"), before this it alternated on a 41,000 year cycle. Both these period lengths are the same as Milankovitch cycles. These cores suggest that today's temperature is higher than almost all of that of the Quaternary (the last 2.6 Million years). *Source:* *Jo Weber*

The changes in climate recorded in ice sheets are thought to be worldwide. The same climate changes observed in Antarctica are also found in cores taken from Greenland, which is on the other side of the Earth. Isotope data can also be taken from sediment cored from the ocean floor—all over the planet—and these cores also show the same changes in climate, alternating between cold and warm. Because ocean sediment is deposited over millions of years, the sediment can give an indication of the climate across the whole of the Quaternary and beyond. Figure 9.3.4 shows how temperature has changed over time (blue line), compared with today (dashed line). The temperature has, on average, gotten colder over the Quaternary, but it also appears to oscillate between warm and cold periods. We'll investigate these periodic changes in the next section of this chapter.

As falling snow accumulates on the ground, tiny bubbles of air become trapped in it. These bubbles are retained as the snow transforms to ice, and constitute tiny samples of the ancient atmosphere that can be analyzed to find out if the changes in temperature (as recorded in the oxygen isotopes) are related to changes in the atmosphere. The temperature recorded by the isotopes in the ice is directly related to the amount of carbon dioxide in the trapped air (Figure 9.3.5): the times with higher carbon dioxide are also times of high temperature.

Falling snow also captures and entombs atmospheric dust, which is topsoil born aloft by the wind, and which is especially prevalent during droughts. The fact that more dust occurs in the ice accumulated during cold periods suggests that the glacial climate was dry, as well as cold.

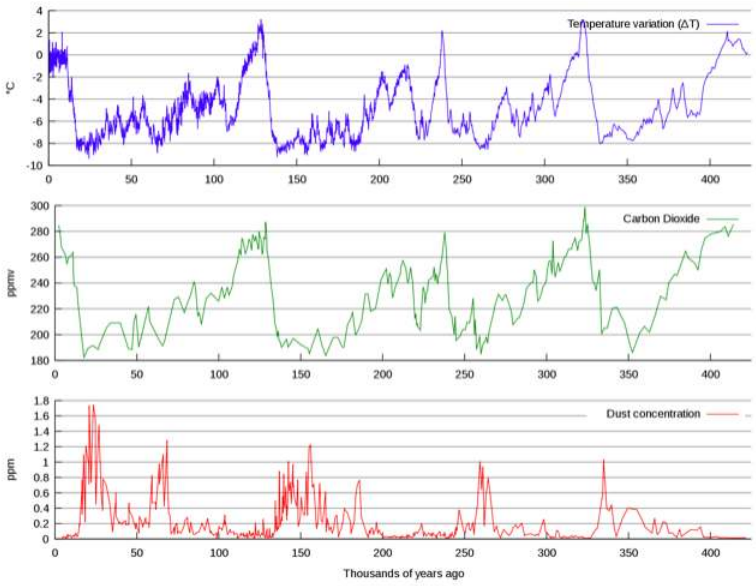


Figure 9.3.5 Vostok Petit Data. These graphs depict how changes in temperature—inferred from changes in isotope ratios (blue line)--correspond to changes in atmospheric carbon dioxide (green line) and dust (red line) over the last 400,000 years as recorded in an ice core extracted from Antarctica. Carbon dioxide varies directly with temperature – the warmer the climate the higher the carbon dioxide level. Atmospheric dust is highest during the coolest periods (such as 25,000 and 150,000 years ago). *Source: William M. Connolley produced figure using data from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Paleoclimatology branch, Vostok Ice Core Data.*



Figure 9.3.6 Ice Age Earth- an artist's impression of the Earth during an ice age. Note that the Northern parts of North America and Europe (including Canada and Scandinavia) are entirely covered by ice-sheets. *Source: Itti*

During the Quaternary, the Earth has cycled between glacial periods (sometimes referred to as "ice ages") and interglacial periods. The ice was at its most recent extreme around 20,000 years ago in a period known as the last glacial maximum, or LGM. As we can see from the ice core record, the Quaternary climate is usually cold (see Figure 9.3.3), with long periods of cold punctuated with shorter (10,000 year long, or so) periods of warmer conditions, like those we experience today. In many ways, our current climate is exceptional—for most of human existence, the Earth has been a much colder place.

What was the Earth like during these glacial periods? Almost all the world was cold; average temperatures were around 6 ^{o}C (-13 ^{o}F) colder than today. Such conditions allow ice sheets to grow—much of North America, Asia and Europe were covered under mile-thick ice (see Figure 9.3.3). Because this ice was made of water that was once in the oceans, sea levels were much lower. At the LGM, sea level was about 120 meters (or about 400 feet) lower than it is today. As the seas retreated, the continents grew larger, creating land bridges that joined Asia with North America, Britain with Europe, and Australia with Papua New Guinea.

During glacial periods the climate was also much drier, as evidenced by the increase in atmospheric dust (Figure 9.3.5). The lands at and near the poles were covered with ice, and dry grasslands occupied areas where temperate forests occur today. Deserts were much larger than they are now, and tropical rainforests, having less water and less warmth, were small. The animals and plants of glacial periods were different in their distribution than they are today, as they were adapted to these different conditions. Fossils of

Mastodons (Figure 9.3.7) have been found from all across what is now the United States, including from Florida, which currently enjoys a subtropical climate.



Figure 9.3.7 An artist's impression of a Knight Mastodon, an elephant-like mammal with a thick wooly coat. Mastodon fossils dating from past glacial periods have been found across North America—from Florida to Alaska. *Source: Charles R. Knight*

During glacial periods humans would have been unable to occupy the globe as they do today because all landmasses experienced different climactic conditions. Some countries of the present could not exist, as they would be almost completely covered by ice. As examples, look for Canada, Iceland and The United Kingdom in Figure 9.3.9.

Milankovitch Cycles

Why has the Earth cycled through hot and cold climates throughout the Quaternary? As we learned in the previous module, the Earth's climate is controlled by several different factors—insolation, greenhouse gases, and albedo are all important. Scientists believe that changes in insolation are responsible for these climate swings, and the insolation varies as a result of wobbles in the Earth's orbit.

The Earth's orbit is not fixed – it changes regularly over time. These periodic changes in Earth's orbit named are referred to as Figure 9.3.8, and are illustrated in Figure 9.3.8. Changes in the Earth's orbit alter the pattern of insolation that the Earth receives. There are three principle ways in which the Earth's orbit varies:

1. Eccentricity (or *Orbital shape*): The Earth's orbit is not perfectly circular, but instead follows an ellipse. This means that the Earth is, through the course of the year, sometimes closer and sometimes further away from the Sun. Currently, the Earth is closest to the Sun in early January, and furthest from the Sun in Early July. This changes the amount of insolation by a few percent, so Northern Hemisphere seasons are slightly milder than they would be if the orbital was circular (cooler summers and warmer winters). The orbital shape changes over time: the Earth moves between being nearly circular and being mildly elliptical. There are two main periods over which this change occurs, one takes around 100,000 years (this is the time over which the orbit goes from being circular, to elliptic, and back to circular), another takes around 400,000 years.
2. Axial Tilt (or Obliquity): The Earth axis spins at an angle to its orbit around the Sun – currently this angle is 23.5 degrees (this angle is known as the *axial tilt*). This difference in orbit creates the seasons (as each hemisphere takes turns being tilted towards and away from the Sun over the course of the year). If the axis of spin lined up with the direction of the Earth's orbit (so that the tilt angle was zero) there would be no seasons! This axial tilt also changes over time, varying between 22.1 and 24.5 degrees. The larger the angle, the larger the temperature difference between summer and winter. It takes about 41,000 year for the axial tilt to change from one extreme to the other, and back again. Currently, the axial tilt is midway between the two extremes and is decreasing—which will make the seasons weaker (cooler summers and warmer winters) over the next 20,000 years.
3. Axial Precession: The direction of Earth's axis of rotation also changes over time relative to the stars. Currently, the North Pole points towards the star Polaris, but the axis of rotation cycles between pointing to that star and the star Vega. This impacts the Earth's climate as it determines when the seasons occur in Earth's orbit. When the axis is pointing at Vega, the Northern Hemisphere's peak summer is in January, not July. If this were true today, it would mean that the Northern Hemisphere would experience more extreme seasons, because January is when the Earth is closest to the Sun (as discussed above in eccentricity). This cycle takes around 20,000 years to complete.

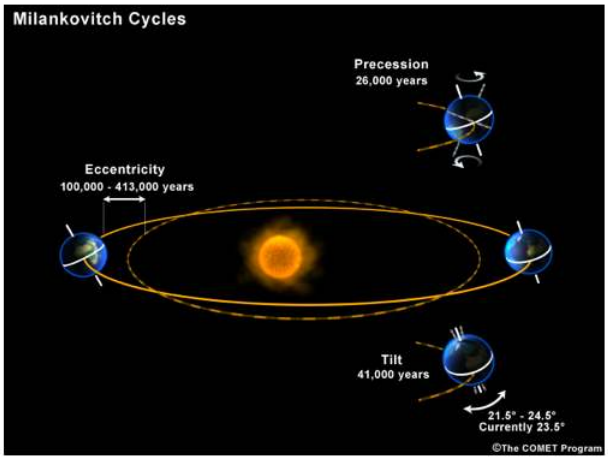


Figure 8. Milankovitch Cycles Illustration of the three variables in Earth's orbit, with periods of variation marked. *Source:* *COMET® at the University Corporation for Atmospheric Research (UCAR) pursuant to a Cooperative Agreements with the National Oceanic and Atmospheric Administration, U.S. Department of Commerce. ©1997-2009 University Corporation for Atmospheric Research. All Rights Reserved.*

The three cycles described above have different periods, all of which are long by human standards: 20,000, 40,000, 100,000 and 400,000 years. If we look at the temperature data from ice and sediment cores, we see that these periods are reflected in Earth's climate. In the last million or so years, the 100,000-year eccentricity in the orbit has determined the timing of glaciations, and before that the 40,000-year axial tilt was dominant (Figure 9.3.8). These cycles have been important for a long time; geologists have even found evidence of these periods in rocks that are hundreds of millions of years old.

But how do the Milankovitch Cycles change our climate? These orbital cycles do not have much impact on the *total* insolation the Earth receives: they change only the *timing* of that insolation. Since the total insolation does not change, these orbital variations have the power to make the Earth's seasons stronger or weaker, but the average annual temperature should stay the same. The best explanation for long term changes in average annual temperature is that the Milankovitch cycles initiate a positive feedback that amplifies the small change in insolation.

Insolation and the Albedo Feedback

Today, the Earth's orbit is not very eccentric (it is almost circular), but at the beginning of each of the recent ice age periods, the orbit was much more elliptical. This meant that the Earth was further away from the sun during the northern hemisphere summers, reducing the total insolation. Lower insolation meant that the summer months were milder than they would otherwise be, with cooler temperatures. Summer temperatures were also lower when the Earth's axial tilt was smaller, so the two different orbital parameters could reinforce one another's effects, in this case producing especially mild summers.

It is thought that these mild northern summers produced an albedo feedback that made the whole planet slip into an ice age. The northern hemisphere has continents near the poles—Europe, Asia, and North America. Today, these continents have largely temperate climates. During the winter, snow falls across much of the land (see Figure 9.3.9 in the previous module) only to melt during the summer months. If the summers are not hot enough to melt all the snow and ice, glaciers can advance, covering more of the land. Because ice has a high albedo, more sunlight is reflected than before, and the Earth is made cooler. This creates a positive feedback, as the cooler conditions allow the ice to advance further—which, in turn, increases the albedo and cools the Earth! Eventually, a large proportion of the northern continents became covered in ice (Figure 9.3.9).

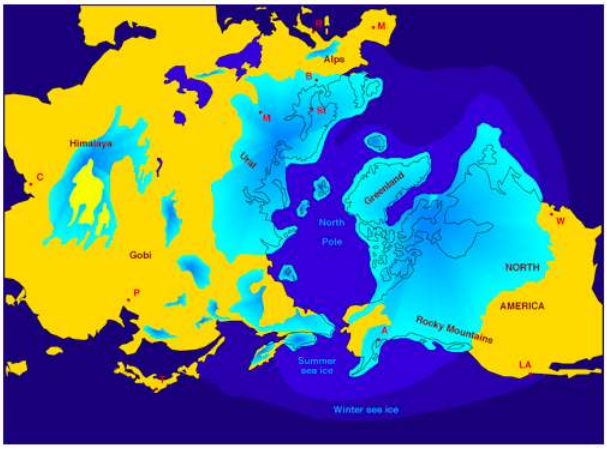


Figure 9.3.9 Glacial coverage (light blue) of the northern hemisphere during the ice ages. *Source: Hannes Grobe*

This positive feedback process works in the other direction, as well. The interglacial periods are ushered in when the orbital parameters create summers that are unusually warm, which melts some of the ice. When the ice sheets shrink, the Earth's albedo decreases, which further warms the system. The giant northern ice sheets shriveled up in a few thousand years as warm summers and decreasing albedo worked together.

These cycles of alternating cooling and warming are also related to changes in the amount of greenhouse gases in the atmosphere. As we observed in Figure 9.3.5, the climate contains higher levels of carbon dioxide during interglacial periods. Although this appears to make sense—carbon dioxide is a greenhouse gas, and so should produce warmer climates—it is also a puzzle, because it is not clear how changes in Milankovitch cycles lead to higher levels of carbon dioxide in the atmosphere. It is clear that these changes in carbon dioxide are important in making the change in temperature between interglacial and glacial periods so extreme. Several different hypotheses have been proposed to explain why glacial periods produce lower levels of carbon dioxide (it may be related to how the physical changes influence the Earth's ecosystems ability to absorb carbon dioxide: perhaps lower sea levels increase the nutrient supply in the ocean, or the drop in sea level destroys coral reefs, or iron-rich dust from new deserts fertilizes the oceans) but further work on this question remains to be done.

It is a concern for all of us that there are gaps in our understanding of how the feedbacks between insolation, albedo and greenhouse gases operate, as it makes it hard to predict what the consequences of any changes in the climate system might lead to. The current level of atmospheric carbon dioxide is unprecedented in human experience; it is at the highest level ever recorded in the Quaternary. Will the current increase in greenhouse gases lead to a positive feedback, warming the Earth even more?

Review Questions

1. In the text, we discuss how polar ice has a smaller ^{18}O to ^{16}O ratio (that is, it has proportionally less heavy isotope water) than ocean water does. Hydrogen also has isotopes, the two most common being hydrogen-1 (^{1}H) and hydrogen-2 (^{2}H, also known as deuterium). Water is made up of both hydrogen and oxygen, and scientists analyze both elements when examining ice cores. Do you predict that polar ice sheets would have a higher ratio or a lower ratio of ^{1}H to ^{2}H than ocean water? Will colder global temperatures increase or decrease the amount of ^{2}H in polar ice?
2. In the text, we discuss how polar ice has a smaller ^{18}O to ^{16}O ratio (that is, it has proportionally less heavy-isotope water) when the climate is cooler. We also discuss how changes in the ratio of ^{18}O to ^{16}O ratio in sediment cores can also be used to determine the climate's average temperature. In ocean sediments, the ratio of ^{18}O to ^{16}O increases when the climate is cooler (that is, it has proportionally more heavy isotope water). Explain why isotope ratios in ocean sediment have the opposite reaction to those in polar ice.
3. There are three different ways in which the Earth's orbit changes through time. What combination of orbital parameters would be most likely to start an ice age? (Hint: Ice ages require cool northern summers.)

Resources

Do you want to know more about how ice cores are extracted and analyzed? NASA's Earth Observatory has details about the practical issues of drilling ice cores (deep ice needs to "relax" for as long as a year at the surface before being cut open – or it can

shatter!) and how chemical data is interpreted. Go to http://earthobservatory.nasa.gov/Features/Paleoclimatology_IceCores/ for an in-depth article with great links.

Glossary

axial precession
The movement in the axis of rotation, which change in the direction of Earth's axis of rotation relative to the stars.

axial tilt
The angle between a planet's axis of rotation and the line perpendicular to the plane in which it orbits. The Earth's current axial tilt is 23.5 degrees.

eccentricity
A measure of how much an ellipse departs from circularity.

glacial period
A long period of time in which ice -sheets and glaciers are advanced in their extent.

ice sheets
Glaciers big enough to cover a continent. Currently, ice sheets are found in Antarctica and Greenland, but during glacial periods, ice sheets have covered other land masses, including North America.

interglacial period
The warm periods of the Quaternary in which glaciers and ice-sheets retreat. These occur between the longer glacial periods.

isotopes
Atoms that have same number of protons but different numbers of neutrons. This means that they are the same element (e.g. oxygen), have the same chemical properties, but different masses.

last glacial maximum
The time at which ice sheets were at their greatest extent during the latest glacial period.

milankovitch cycles
Periodic variations in the Earth's orbit that influence its climate. These cycles are named after Milutin Milankovitch, a mathematician who quantified the theory.

quaternary period
The most recent geological period, spanning the time from 2.6 million years ago to today.

obliquity
See Axial Tilt.

proxy data
Information about the climate that accumulates through natural phenomena.

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9.4: Causes of Global Climate Change

Learning Objectives

- Explain the drivers of climate change, past and present

Current and Past Drivers of Global Climate Change

Since it is not possible to go back in time to directly observe and measure climate, scientists use indirect evidence to determine the drivers, or factors, that may be responsible for climate change. The indirect evidence includes data collected using ice cores, boreholes (narrow shafts bored into the ground), tree rings, glacier lengths, pollen remains, and ocean sediments. The data shows a correlation between the timing of temperature changes and drivers of climate change. Before the Industrial Era (pre-1780), there were three drivers of climate change that were not related to human activity or atmospheric gases: the Milankovitch cycles, solar intensity, and volcanic eruptions.

Natural Causes of Climate Change

The Milankovitch cycles describe how slight changes in the earth's orbit affect the earth's climate. The length of the Milankovitch cycles ranges between 19,000 and 100,000 years. In other words, one could expect to see some predictable changes in the earth's climate associated with changes in the earth's orbit at a minimum of every 19,000 years.

The variation in the sun's intensity is the second natural factor responsible for climate change. Solar intensity is the amount of solar power or energy the sun emits in a given length of time. There is a direct relationship between solar intensity and temperature: as solar intensity increases (or decreases), the earth's temperature correspondingly increases (or decreases). Changes in solar intensity have been proposed as one of several possible explanations for the Little Ice Age.

Finally, volcanic eruptions are a third natural driver of climate change. Volcanic eruptions can last a few days, but the solids and gases released during an eruption can influence the climate over a period of a few years, causing 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.

Human Activity-Related Causes of Climate Change

Greenhouse gases are probably the most significant drivers of the climate. When heat energy from the sun strikes the earth, gases known as greenhouse gases trap the heat in the atmosphere, similar to how the glass panes of a greenhouse keep heat from escaping. The greenhouse gases that affect earth include carbon dioxide, methane, water vapor, nitrous oxide, and ozone. Approximately half of the radiation from the sun passes through these gases in the atmosphere, striking the earth. This radiation is converted into thermal radiation on the earth's surface; a portion of that energy is re-radiated into the atmosphere. Greenhouse gases, however, reflect much of the thermal energy back to the earth's surface. The more greenhouse gases there are in the atmosphere, the more thermal energy is reflected back to the earth's surface. Greenhouse gases, as they absorb and emit radiation, are an important factor in the greenhouse effect, or the warming of earth due to carbon dioxide and other greenhouse gases in the atmosphere.



Figure 9.4.1: Greenhouse gasses: The burning of fossil fuels in industry and by vehicles releases carbon dioxide and other greenhouse gases into the atmosphere.

Beginning recently, atmospheric carbon dioxide concentrations have increased beyond the historical maximum of 300 ppm. The current increases in atmospheric carbon dioxide have happened very quickly: in a matter of hundreds of years rather than thousands of years. A key factor that must be recognized when comparing the historical data and the current data is the presence of modern human society. No other driver of climate change has yielded changes in atmospheric carbon dioxide levels at this rate or to this magnitude.

Human activity releases carbon dioxide and methane, two of the most important greenhouse gases, into the atmosphere in several ways. The primary mechanism that releases carbon dioxide is the burning of fossil fuels, such as gasoline, coal, and natural gas. Deforestation, cement manufacture, animal agriculture, the clearing of land, and the burning of forests are other human activities that release carbon dioxide. Methane (CH_4) is produced when bacteria break down organic matter under anaerobic conditions (i.e., without oxygen), which can happen when organic matter is trapped underwater, as in rice paddies, or in the intestines of herbivores. Methane can also be released from natural gas fields and the decomposition that occurs in landfills. Another source of methane is the melting of clathrates: frozen chunks of ice and methane found at the bottom of the ocean. When water warms, these chunks of ice melt, releasing methane. As the ocean's water temperature increases, the rate at which clathrates melt is increasing, releasing even more methane. This leads to increased levels of methane in the atmosphere, which further accelerates the rate of global warming. This is an example of the positive feedback loop that is leading to the rapid rate of increase of global temperatures.

Key Points

- Data show a correlation between the timing of temperature changes and drivers of climate change.
- Prior to the Industrial Era (pre-1780), there were three drivers of climate change that were not related to human activity: Milankovitch cycles, sun intensity, and volcanic eruptions.
- Greenhouse gases, probably the most significant drivers of the climate, include carbon dioxide, methane, water vapor, nitrous oxide, and ozone.
- Human activity, such as the burning of fossil fuels, releases carbon dioxide and methane, two of the most important greenhouse gases, into the atmosphere.
- Deforestation, cement manufacture, animal agriculture, the clearing of land, and the burning of forests are other human activities that release carbon dioxide.

Key Terms

- **Milankovitch cycle**: any of the three cyclic variations in the earth's orbit around the sun, respectively the obliquity of its axis, the precession of the equinoxes, and the eccentricity of its orbit

- **greenhouse gas**: any gas, such as carbon dioxide, that contributes to the greenhouse effect (continued warming) when released into the atmosphere
- **greenhouse effect**: the process by which a planet is warmed by its atmosphere

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9.5: Evidence of Global Climate Change

Learning Objectives

- Evaluate the evidence for global climate change

Global Climate Change

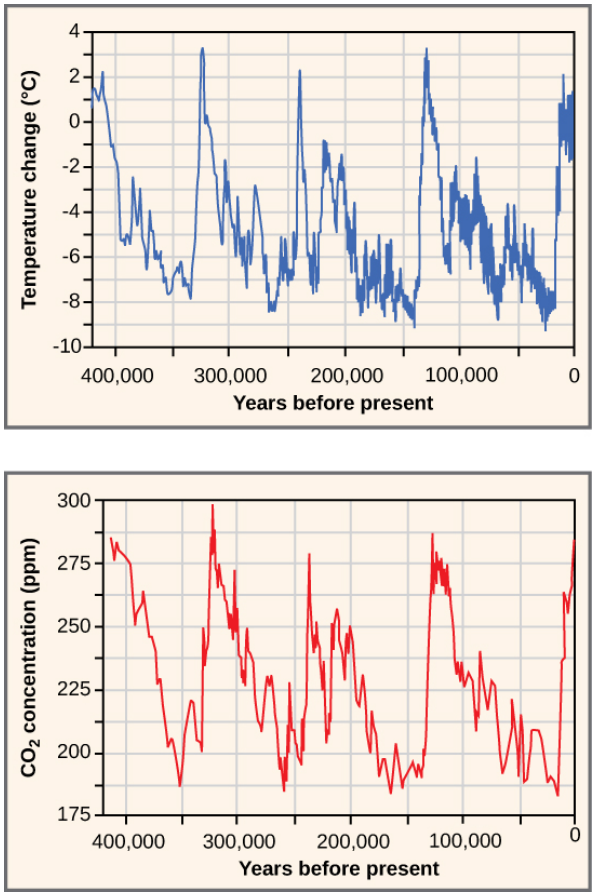


Figure 9.5.1: Measuring historical climate change: By measuring the amount of CO2 trapped in ice, scientists can determine past atmospheric CO2 concentrations. Temperatures relative to the present are determined from the amount of deuterium (an isotope of hydrogen) present.

Climate change can be understood by approaching three areas of study: (1) evidence of current and past global climate change, (2) causes of past and present-day global climate change, and (3) ancient and current results of climate change.

It is helpful to keep these three different aspects of climate change clearly separated when consuming media reports about global climate change. It is common for reports and discussions about global climate change to confuse the data showing that earth's climate is changing with the factors that drive this 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 climates.

Antarctic ice cores are a key example of such evidence. 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 bubbles of air and other biological evidence that can reveal temperature and carbon dioxide data. Antarctic ice cores have been collected and analyzed to indirectly estimate the temperature of the earth over the past 400,000 years.

Before the late 1800s, the earth had been as much as 9°C cooler and about 3°C warmer. Atmospheric concentration of carbon dioxide also rose and fell in periodic cycles; note the relationship between carbon dioxide concentration and temperature. Carbon dioxide levels in the atmosphere have historically cycled between 180 and 300 parts per million (ppm) by volume.

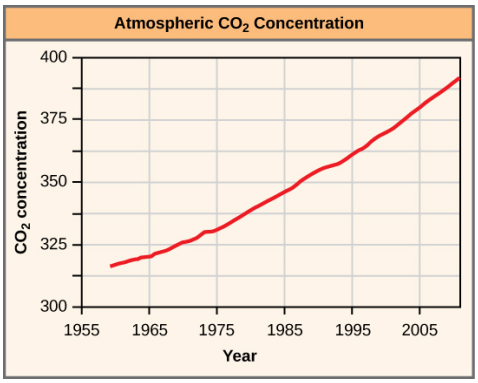


Figure 9.5.1: Climate change and the Industrial Era: The atmospheric concentration of CO2 has risen steadily since the beginning of industrialization.The Industrial Revolution, which began around 1750, was characterized by changes in much of human society. Advances in agriculture increased the food supply, which improved the standard of living for people in Europe and the United States. New technologies were invented, providing jobs and cheaper goods. These new technologies were powered using fossil fuels, especially coal. The Industrial Revolution in the early nineteenth century ushered in the beginning of the Industrial Era, a period when atmospheric carbon dioxide began to rise. When a fossil fuel is burned, carbon dioxide is released.

Two significant temperature anomalies, or irregularities, have occurred in the last 2000 years. These are the Medieval Climate Anomaly (or the Medieval Warm Period) and the Little Ice Age. A third temperature anomaly aligns with the Industrial Era. The Medieval Climate Anomaly occurred between 900 and 1300 AD. During this time period, many climate scientists think that slightly-warmer conditions prevailed in many parts of the world; the higher-than-average temperature changes varied between 0.10 °C and 0.20 °C above the norm. Although 0.10 °C does not seem large enough to produce any noticeable change, it did free seas of ice. Because of this warming, the Vikings were able to colonize Greenland.

The Little Ice Age was a cold period that occurred between 1550 AD and 1850 AD. During this time, a slight cooling of a little less than 1 °C was observed in North America, Europe, and possibly other areas of the world. This 1 °C change is a seemingly-small deviation in temperature (as was observed during the Medieval Climate Anomaly); however, it also resulted in noticeable changes. Historical accounts reveal a time of exceptionally-harsh winters with much snow and frost.

Key Points

- Climate change can be understood by approaching three areas of study: (1) current and past global climate change, (2) causes of past and present-day global climate change, and (3) ancient and current results of climate change.
- Since we cannot go back in time to directly measure climatic variables, such as average temperature and precipitation, we must rely on historical evidence of earth's past climate, such as Antarctic ice cores.
- Three significant temperature anomalies, or irregularities, have occurred in the last 2000 years: the Medieval Climate Anomaly (or the Medieval Warm Period), the Little Ice Age, and the Industrial Era.
- With the beginning of the Industrial Era, atmospheric carbon dioxide began to rise.

Key Terms

- **fossil fuel**: any fuel derived from hydrocarbon deposits such as coal, petroleum, natural gas, and, to some extent, peat; these fuels are irreplaceable; their burning generates the greenhouse gas carbon dioxide

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9.6: Past and Present Effects of Climate Change

Learning Objectives

- Describe the effects of current and geological climate change

Documented results of climate change: past and present

Scientists have geological evidence of the consequences of long-ago climate change. Modern-day phenomena, such as retreating glaciers and melting polar ice, cause a continual rise in sea level. Changes in climate can negatively affect organisms.

Geological climate change effects

Global warming has been associated with at least one planet-wide extinction event during the geological past. The Permian extinction event occurred about 251 million years ago toward the end of the roughly 50-million-year-long geological time span known as the Permian period. This geologic time period was one of the three warmest periods in earth's geologic history. Scientists estimate that approximately 70 percent of the terrestrial plant and animal species and 84 percent of marine species became extinct, vanishing forever near the end of the Permian period. Organisms that had adapted to wet and warm climatic conditions, such as annual rainfall of 300–400 cm (118–157 in) and 20 °C–30 °C (68 °F–86 °F) in the tropical wet forest, may not have been able to survive the Permian climate change.

Present climate change effects

A number of global events have occurred that may be attributed to recent climate change during our lifetimes. Glacier National Park in Montana, among others, is undergoing the retreat of many of its glaciers, a phenomenon known as glacier recession. In 1850, the area contained approximately 150 glaciers. By 2010, however, the park contained only about 24 glaciers greater than 25 acres in size. One of these glaciers is the Grinnell Glacier at Mount Gould. Between 1966 and 2005, the size of Grinnell Glacier shrank by 40 percent. Similarly, the mass of the ice sheets in Greenland and the Antarctic is decreasing: Greenland lost 150–250 km^3 of ice per year between 2002 and 2006. In addition, the size and thickness of the Arctic sea ice is decreasing.



Figure 9.6.1: Glacial recession: The effect of global warming can be seen in the continuing retreat of Grinnel Glacier. The loss of a glacier results in the loss of summer meltwaters, sharply reducing seasonal water supplies and severely affecting local ecosystems.

This loss of ice is leading to rises in the global sea level. On average, the sea is rising at a rate of 1.8 mm per year. However, between 1993 and 2010, the rate of sea-level increase ranged between 2.9 and 3.4 mm per year. A variety of factors affect the volume of water in the ocean, including the temperature of the water (the density of water is related to its temperature) and the amount of water found in rivers, lakes, glaciers, polar ice caps, and sea ice. As glaciers and polar ice caps melt, there is a significant contribution of liquid water that was previously frozen.

In addition to some abiotic conditions changing in response to climate change, many organisms are also being affected by the changes in temperature. Temperature and precipitation play key roles in determining the geographic distribution and phenology of plants and animals. Phenology is the study of the effects of climatic conditions on the timing of periodic lifecycle events, such as flowering in plants or migration in birds. Researchers have shown that 385 plant species in Great Britain are flowering 4.5 days sooner than was recorded during the previous 40 years. In addition, insect-pollinated species were more likely to flower earlier than wind-pollinated species. The impact of changes in flowering date would be mitigated if the insect pollinators emerged earlier. This

mismatched timing of plants and pollinators could result in injurious ecosystem effects because, for continued survival, insect-pollinated plants must flower when their pollinators are present.

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Key Points

- Global warming has been associated with at least one planet-wide extinction event during the geological past; scientists estimate that during the Permian period, approximately 70 percent of the terrestrial plant and animal species along with 84 percent of marine species became extinct.
- Glacier recession and melting ice caps are direct effects of current global climate change, ultimately leading to higher global sea levels; as glaciers and polar ice caps melt, there is a significant contribution of liquid water that was previously frozen.
- Changes in temperature and precipitation are causing plants to flower earlier, before their insect pollinators have emerged; mismatched timing of plants and pollinators could result in injurious ecosystem effects.
- This mismatched timing of plants and pollinators could result in injurious ecosystem effects because, for continued survival, insect-pollinated plants must flower when their pollinators are present.

Key Terms

- **phenology**: the study of the effect of climate on periodic biological phenomena
- **Permian**: of a geologic period within the Paleozoic era; comprises the Cisuralian, Guadalupian, and Lopingian epochs from about 280 to 248 million years ago

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9.7: Climate Change

Earth's Temperature is a Balancing Act

Earth's temperature depends on the balance between energy entering and leaving the planet. When incoming energy from the sun is absorbed, Earth warms. When the sun's energy is reflected back into space, Earth avoids warming. When energy is released from Earth into space, the planet cools. Many factors, both natural and human, can cause changes in Earth's energy balance, including:

- Changes in the greenhouse effect, which affects the amount of heat retained by Earth's atmosphere;
- Variations in the sun's energy reaching Earth;
- Changes in the reflectivity of Earth's atmosphere and surface.

Scientists have pieced together a picture of Earth's climate, dating back hundreds of thousands of years, by analyzing a number of indirect measures of climate such as ice cores, tree rings, glacier size, pollen counts, and ocean sediments. Scientists have also studied changes in Earth's orbit around the sun and the activity of the sun itself.

The historical record shows that the climate varies naturally over a wide range of time scales. In general, climate changes prior to the Industrial Revolution in the 1700s can be explained by natural causes, such as changes in solar energy, volcanic eruptions, and natural changes in greenhouse gas (GHG) concentrations. Recent changes in climate**,** however, cannot be explained by natural causes alone. Research indicates that natural causes are very unlikely to explain most observed warming, especially warming since the mid-20th century. Rather, it is extremely likely that human activities, especially our combustion of fossil fuels, explains most of that warming. The scientific consensus is clear: through alterations of the carbon cycle, humans are changing the global climate by increasing the effects of something known as the greenhouse effect.

The Greenhouse Effect Causes the Atmosphere to Retain Heat

Gardeners that live in moderate or cool environments use greenhouses because they trap heat and create an environment that is warmer than outside temperatures. This is great for plants that like heat, or are sensitive to cold temperatures, such as tomato and pepper plants. Greenhouses contain glass or plastic that allow visible light from the sun to pass. This light, which is a form of energy, is absorbed by plants, soil, and surfaces and heats them. Some of that heat energy is then radiated outwards in the form of infrared radiation, a different form of energy. Unlike with visible light, the glass of the greenhouse blocks the infrared radiation, thereby trapping the heat energy, causing the temperature within the greenhouse to increase.

The same phenomenon happens inside a car on a sunny day. Have you ever noticed how much hotter a car can get compared to the outside temperature? Light energy from the sun passes through the windows and is absorbed by the surfaces in the car such as seats and the dashboard. Those warm surfaces then radiate infrared radiation, which cannot pass through the glass. This trapped infrared energy causes the air temperatures in the car to increase. This process is commonly known as the **greenhouse effect**.

The greenhouse effect also happens with the entire Earth. Of course, our planet is not surrounded by glass windows. Instead, the Earth is wrapped with an atmosphere that contains **greenhouse gases** (GHGs). Much like the glass in a greenhouse, GHGs allow incoming visible light energy from the sun to pass, but they block infrared radiation that is radiated from the Earth towards space (Figure 9.7.1). In this way, they help trap heat energy that subsequently raises air temperature. Being a greenhouse gas is a physical property of certain types of gases; because of their molecular structure they absorb wavelengths of infrared radiation, but are transparent to visible light. Some notable greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4).

GHGs act like a blanket, making Earth significantly warmer than it would otherwise be. Scientists estimate that average temperature on Earth would be -18º C without naturally-occurring GHGs.

What is Global Warming?
Global warming refers to the recent and ongoing rise in global average temperature near Earth's surface. It is caused mostly by increasing concentrations of greenhouse gases in the atmosphere. Global warming is causing climate patterns to change. However, global warming itself represents only one aspect of climate change.
What is Climate Change?
Climate change refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among other effects, that occur over several decades or longer.

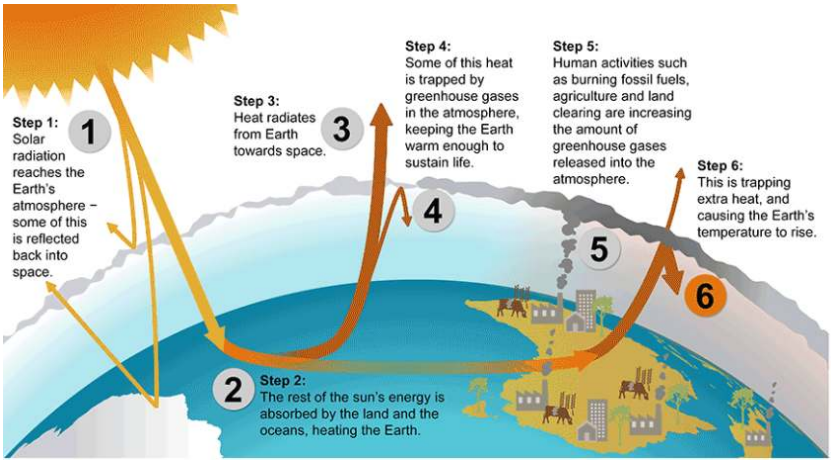


Figure 9.7.1. Enhanced Greenhouse Effect

The Main Greenhouse Gasses

The most important GHGs directly emitted by humans include CO_2 and methane. **Carbon dioxide** (CO_2) is the primary greenhouse gas that is contributing to recent global climate change. CO_2 is a natural component of the carbon cycle, involved in such activities as photosynthesis, respiration, volcanic eruptions, and ocean-atmosphere exchange. Human activities, primarily the burning of fossil fuels and changes in land use, release very large amounts of CO_2 to the atmosphere, causing its concentration in the atmosphere to rise.

Atmospheric CO_2 concentrations have increased by 45% since pre-industrial times, from approximately 280 parts per million (ppm) in the 18th century to 408 ppm in 2018. The current CO_2 level is higher than it has been in at least 800,000 years, based on evidence from ice cores that preserve ancient atmospheric gases. Human activities currently release over 30 billion tons of CO_2 into the atmosphere every year. While some some volcanic eruptions released large quantities of CO_2 in the distant past, the U.S. Geological Survey (USGS) reports that human activities now emit more than 135 times as much CO_2 as volcanoes each year. This human-caused build-up of CO_2 in the atmosphere is like a tub filling with water, where more water flows from the faucet than the drain can take away.

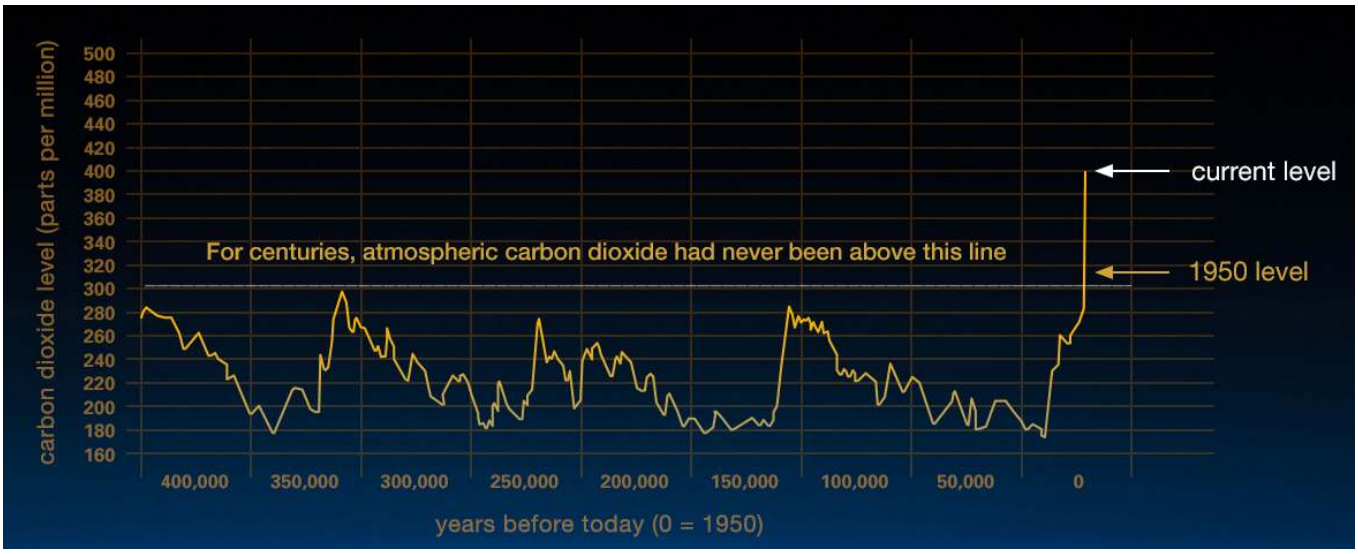


Figure 9.7.2. This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO_2 has increased since the Industrial Revolution. (Credit: Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO2 record.)

Methane (CH_4) is produced through both natural and human activities. For example, wetlands, agricultural activities, and fossil fuel extraction and transport all emit CH_4. Methane is more abundant in Earth's atmosphere now than at any time in at least the past 650,000 years. Due to human activities, CH_4 concentrations increased sharply during most of the 20th century and are now more than two and-a-half times pre-industrial levels. In recent decades, the rate of increase has slowed considerably.

Other Greenhouse Gasses

Water vapor is the most abundant greenhouse gas and also the most important in terms of its contribution to the natural greenhouse effect, despite having a short atmospheric lifetime. Some human activities can influence local water vapor levels. However, on a global scale, the concentration of water vapor is controlled by temperature, which influences overall rates of evaporation and precipitation. Therefore, the global concentration of water vapor is not substantially affected by direct human emissions.

Ground-level ozone (O_3), which also has a short atmospheric lifetime, is a potent greenhouse gas. Chemical reactions create ozone from emissions of nitrogen oxides and volatile organic compounds from automobiles, power plants, and other industrial and commercial sources in the presence of sunlight (as discussed in section 10.1). In addition to trapping heat, ozone is a pollutant that can cause respiratory health problems and damage crops and ecosystems.

Changes in the Sun's Energy Affect how Much Energy Reaches Earth

Climate can be influenced by natural changes that affect how much solar energy reaches Earth. These changes include changes within the sun and changes in Earth's orbit. Changes occurring in the sun itself can affect the intensity of the sunlight that reaches Earth's surface. The intensity of the sunlight can cause either warming (during periods of stronger solar intensity) or cooling (during periods of weaker solar intensity). The sun follows a natural 11-year cycle of small ups and downs in intensity, but the effect on Earth's climate is small. Changes in the shape of Earth's orbit as well as the tilt and position of Earth's axis can also affect the amount of sunlight reaching Earth's surface.

Changes in the sun's intensity have influenced Earth's climate in the past. For example, the so-called "**Little Ice Age**" between the 17th and 19th centuries may have been partially caused by a low solar activity phase from 1645 to 1715, which coincided with cooler temperatures. The Little Ice Age refers to a slight cooling of North America, Europe, and probably other areas around the globe. Changes in Earth's orbit have had a big impact on climate over tens of thousands of years. These changes appear to be the primary cause of past cycles of ice ages, in which Earth has experienced long periods of cold temperatures (ice ages), as well as shorter interglacial periods (periods between ice ages) of relatively warmer temperatures.

Changes in solar energy continue to affect climate. However, solar activity has been relatively constant, aside from the 11-year cycle, since the mid-20th century and therefore does not explain the recent warming of Earth. Similarly, changes in the shape of

Earth's orbit as well as the tilt and position of Earth's axis affect temperature on relatively long timescales (tens of thousands of years), and therefore cannot explain the recent warming.

Changes in Reflectivity Affect How Much Energy Enters Earth's System

When sunlight energy reaches Earth it can be reflected or absorbed. The amount that is reflected or absorbed depends on Earth's surface and atmosphere. Light-colored objects and surfaces, like snow and clouds, tend to reflect most sunlight, while darker objects and surfaces, like the ocean and forests, tend to absorb more sunlight. The term **albedo** refers to the amount of solar radiation reflected from an object or surface, often expressed as a percentage. Earth as a whole has an albedo of about 30%, meaning that 70% of the sunlight that reaches the planet is absorbed. Sunlight that is absorbed warms Earth's land, water, and atmosphere.

Albedo is also affected by aerosols. **Aerosols** are small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight. Unlike greenhouse gases (GHGs), the climate effects of aerosols vary depending on what they are made of and where they are emitted. Those aerosols that reflect sunlight, such as particles from volcanic eruptions or sulfur emissions from burning coal, have a cooling effect. Those that absorb sunlight, such as black carbon (a part of soot), have a warming effect.

Natural changes in albedo, like the melting of sea ice or increases in cloud cover, have contributed to climate change in the past, often acting as feedbacks to other processes. Volcanoes have played a noticeable role in climate. Volcanic particles that reach the upper atmosphere can reflect enough sunlight back to space to cool the surface of the planet by a few tenths of a degree for several years. Volcanic particles from a single eruption do not produce long-term change because they remain in the atmosphere for a much shorter time than GHGs.

Human changes in land use and land cover have changed Earth's albedo. Processes such as deforestation, reforestation, desertification, and urbanization often contribute to changes in climate in the places they occur. These effects may be significant regionally, but are smaller when averaged over the entire globe.

Scientific Consensus: Global Climate Change is Real

The **Intergovernmental Panel on Climate Change** (IPCC) was created in 1988 by the United Nations Environment Programme and the World Meteorological Organization. It is charged with the task of evaluating and synthesizing the scientific evidence surrounding global climate change. The IPCC uses this information to evaluate current impacts and future risks, in addition to providing policymakers with assessments. These assessments are released about once every every six years. The most recent report, the 5th Assessment, was released in 2013. Hundreds of leading scientists from around the world are chosen to author these reports. Over the history of the IPCC, these scientists have reviewed thousands of peer-reviewed, publicly available studies. The scientific consensus is clear: global climate change is real and humans are very likely the cause for this change.

Additionally, the major scientific agencies of the United States, including the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), also agree that climate change is occurring and that humans are driving it. In 2010, the US National Research Council concluded that "Climate change is occurring, is very likely caused by human activities, and poses significant risks for a broad range of human and natural systems". Many independent scientific organizations have released similar statements, both in the United States and abroad. This doesn't necessarily mean that every scientist sees eye to eye on each component of the climate change problem, but broad agreement exists that climate change is happening and is primarily caused by excess greenhouse gases from human activities. Critics of climate change, driven by ideology instead of evidence, try to suggest to the public that there is no scientific consensus on global climate change. Such an assertion is patently false.

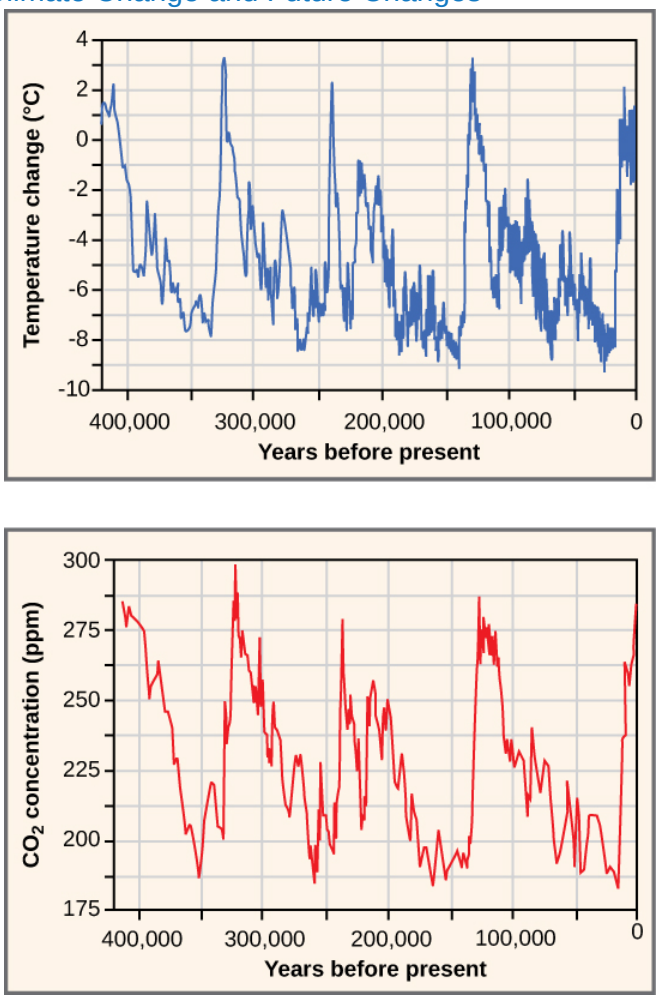


Figure 9.7.3. Ice at the Russian Vostok station in East Antarctica was laid down over the course 420,000 years and reached a depth of over 3,000 m. By measuring the amount of CO_2 trapped in the ice, scientists have determined past atmospheric CO_2 concentrations. Temperatures relative to modern day were determined from the amount of deuterium (an isotope of hydrogen) present.

Greenhouse gas concentrations in the atmosphere will continue to increase unless the billions of tons of anthropogenic emissions each year decrease substantially. Increased concentrations are expected to:

- Increase Earth's average temperature,
- Influence the patterns and amounts of precipitation,
- Reduce ice and snow cover, as well as permafrost,
- Raise sea level,
- Increase the acidity of the oceans.

These changes will impact our food supply, water resources, infrastructure, ecosystems, and even our own health. The magnitude and rate of future climate change will primarily depend on the following factors:

- The rate at which levels of greenhouse gas concentrations in our atmosphere continue to increase,
- How strongly features of the climate (e.g., temperature, precipitation, and sea level) respond to the expected increase in greenhouse gas concentrations,
- Natural influences on climate (e.g., from volcanic activity and changes in the sun's intensity) and natural processes within the climate system (e.g., changes in ocean circulation patterns).

Past and Present-day GHG Emissions Will Affect Climate Far into the Future

Many greenhouse gases stay in the atmosphere for long periods of time. As a result, even if emissions stopped increasing, atmospheric greenhouse gas concentrations would continue to remain elevated for hundreds of years. Moreover, if we stabilized concentrations and the composition of today's atmosphere remained steady (which would require a dramatic reduction in current greenhouse gas emissions), surface air temperatures would continue to warm. This is because the oceans, which store heat, take many decades to fully respond to higher greenhouse gas concentrations. The ocean's response to higher greenhouse gas concentrations and higher temperatures will continue to impact climate over the next several decades to hundreds of years.

Future Temperature Changes

Climate models project the following key temperature-related changes:

Key Global Projections

- Average global temperatures are expected to increase by 2°F to 11.5°F by 2100, depending on the level of future greenhouse gas emissions, and the outcomes from various climate models.
- By 2100, global average temperature is expected to warm at least twice as much as it has during the last 100 years.
- Ground-level air temperatures are expected to continue to warm more rapidly over land than oceans.
- Some parts of the world are projected to see larger temperature increases than the global average.

Future Precipitation and Storm Events

Patterns of precipitation and storm events, including both rain and snowfall are likely to change. However, some of these changes are less certain than the changes associated with temperature. Projections show that future precipitation and storm changes will vary by season and region. Some regions may have less precipitation, some may have more precipitation, and some may have little or no change. The amount of rain falling in heavy precipitation events is likely to increase in most regions, while storm tracks are projected to shift towards the poles. Climate models project the following precipitation and storm changes:

- Global average annual precipitation through the end of the century is expected to increase, although changes in the amount and intensity of precipitation will vary by region.
- The intensity of precipitation events will likely increase on average. This will be particularly pronounced in tropical and high-latitude regions, which are also expected to experience overall increases in precipitation.
- The strength of the winds associated with tropical storms is likely to increase. The amount of precipitation falling in tropical storms is also likely to increase.
- Annual average precipitation is projected to increase in some areas and decrease in others.

Future Ice, Snowpack, and Permafrost

Arctic sea ice is already declining drastically. The area of snow cover in the Northern Hemisphere has decreased since 1970. Permafrost temperature has increased over the last century, making it more susceptible to thawing. Over the next century, it is expected that sea ice will continue to decline, glaciers will continue to shrink, snow cover will continue to decrease, and permafrost will continue to thaw.

For every 2°F of warming, models project about a 15% decrease in the extent of annually averaged sea ice and a 25% decrease in September Arctic sea ice. The coastal sections of the Greenland and Antarctic ice sheets are expected to continue to melt or slide into the ocean. If the rate of this ice melting increases in the 21st century, the ice sheets could add significantly to global sea level rise. Glaciers are expected to continue to decrease in size. The rate of melting is expected to continue to increase, which will contribute to sea level rise.

Future Sea Level Change

Warming temperatures contribute to sea level rise by expanding ocean water, melting mountain glaciers and ice caps, and causing portions of the Greenland and Antarctic ice sheets to melt or flow into the ocean. Since 1870, global sea level has risen by about 8 inches. Estimates of future sea level rise vary for different regions, but global sea level for the next century is expected to rise at a greater rate than during the past 50 years. The contribution of thermal expansion, ice caps, and small glaciers to sea level rise is relatively well-studied, but the impacts of climate change on ice sheets are less understood and represent an active area of research.

Thus, it is more difficult to predict how much changes in ice sheets will contribute to sea level rise. Greenland and Antarctic ice sheets could contribute an additional 1 foot of sea level rise, depending on how the ice sheets respond.

Regional and local factors will influence future relative sea level rise for specific coastlines around the world. For example, relative sea level rise depends on land elevation changes that occur as a result of subsidence (sinking) or uplift (rising), in addition to things such as local currents, winds, salinity, water temperatures, and proximity to thinning ice sheets. Assuming that these historical geological forces continue, a 2-foot rise in global sea level by 2100 would result in the following relative sea level rise:

- 2.3 feet at New York City
- 2.9 feet at Hampton Roads, Virginia
- 3.5 feet at Galveston, Texas
- 1 foot at Neah Bay in Washington state

Future Ocean Acidification

Ocean acidification is the process of ocean waters decreasing in pH. Oceans become more acidic as carbon dioxide (CO_2) emissions in the atmosphere dissolve in the ocean. This change is measured on the pH scale, with lower values being more acidic. The pH level of the oceans has decreased by approximately 0.1 pH units since pre-industrial times, which is equivalent to a 25% increase in acidity. The pH level of the oceans is projected to decrease even more by the end of the century as CO_2 concentrations are expected to increase for the foreseeable future. Ocean acidification adversely affects many marine species, including plankton, mollusks, shellfish, and corals. As ocean acidification increases, the availability of calcium carbonate will decline. Calcium carbonate is a key building block for the shells and skeletons of many marine organisms. If atmospheric CO_2 concentrations double, coral calcification rates are projected to decline by more than 30%. If CO_2 concentrations continue to rise at their current rate, corals could become rare on tropical and subtropical reefs by 2050.

Spread of Disease

This rise in global temperatures will increase the range of disease-carrying insects and the viruses and pathogenic parasites they harbor. Thus, diseases will spread to new regions of the globe. This spread has already been documented with dengue fever, a disease the affects hundreds of millions per year, according to the World Health Organization. Colder temperatures typically limit the distribution of certain species, such as the mosquitoes that transmit malaria, because freezing temperatures destroy their eggs.

Not only will the range of some disease-causing insects expand, the increasing temperatures will also accelerate their lifecycles, which allows them to breed and multiply quicker, and perhaps evolve pesticide resistance faster. In addition to dengue fever, other diseases are expected to spread to new portions of the world as the global climate warms. These include malaria, yellow fever, West Nile virus, zika virus, and chikungunya.

Climate change affects everyone

Our lives are connected to the climate**.** Human societies have adapted to the relatively stable climate we have enjoyed since the last ice age which ended several thousand years ago. A warming climate will bring changes that can affect our water supplies, agriculture, power and transportation systems, the natural environment, and even our own health and safety.

Carbon dioxide can stay in the atmosphere for nearly a century, on average, so Earth will continue to warm in the coming decades. The warmer it gets, the greater the risk for more severe changes to the climate and Earth's system. Although it's difficult to predict the exact impacts of climate change, what's clear is that the climate we are accustomed to is no longer a reliable guide for what to expect in the future.

We can reduce the risks we will face from climate change**.** By making choices that reduce greenhouse gas pollution, and preparing for the changes that are already underway, we can reduce risks from climate change. Our decisions today will shape the world our children and grandchildren will live in.

You Can Take Action

You can take steps at home, on the road, and in your office to reduce greenhouse gas emissions and the risks associated with climate change. Many of these steps can save you money. Some, such as walking or biking to work, can even improve your health! You can also get involved on a local or state level to support energy efficiency, clean energy programs, or other climate programs.

Suggested Supplementary Reading:

Intergovernmental Panel on Climate Change. 2013. 5th Assessment: Summary for Policymakers. <http://www.ipcc.ch/pdf/assessment-re..._SPM_FINAL.pdf>

NASA. 2018. Global Climate Change: Vital Signs of the Planet. Website. <https://climate.nasa.gov/>

This website by NASA provides a multi-media smorgasbord of engaging content. Learn about climate change using data collected by NASA satellites and more.

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9.8: Consequences of Climate Change

As part of your assigned reading for this section, read the article “The Coming Storm” by Don Belt published in National Geographic: http://ngm.nationalgeographic.com/pr...desh/belt-text In this section, we will discuss the effects of climate change, both those that have already been observed, as well as future predictions based on scientific climate models (see section 7.5 for a discussion of scientific models). Here, the differences between the terms **global warming** and **climate change** become apparent. Global warming refers to the increase in the average temperature of the Earth’s atmosphere due to elevated greenhouse gas concentrations, heightening the greenhouse effect. We have already observed this increase occurring, as you saw in Figure 7.5.2 from section 7.5. We have also seen, and expect to continue to see, other changes occurring in the **climate** of the Earth. Furthermore, changes have been observed, and we expect to continue to observe, changes in other chemical, physical, and biological aspects of the Earth’s environment. We will only discuss some of the consequences of climate change in this section, including changes in temperature, precipitation, ocean level, and ocean acidity. There are many more changes that have been seen, and are projected to continue in the future. These include: changes in the amount and distribution of ice and snow, changes in seasonality, ecosystem shift, and habitat changes of plant and animal populations, in addition to others. For more information about these consequence of climate change, visit this site: http://www.epa.gov/climatechange/sci...ors/index.html.

Temperature and precipitation

Temperature and **precipitation** are the two most direct impacts on the Earth’s climate due to climate change. By now, you should already understand why an increase in greenhouse gas levels in the atmosphere causes an increase in temperature. But why does it also impact precipitation patterns? As you already know, water vapor is an important component of the Earth’s atmosphere (see Chapter 6). As the air in the troposphere warms and cools, the amount of water vapor that it holds changes dramatically. Here in Georgia, we have very hot and humid summers. The high summer humidity in this region is possible due to the increased capability warm air has to hold water vapor. Simply put, warmer air can hold more water than cooler air. As air cools, its ability to hold water vapor decreases, and any excess water will leave the air as liquid water. A great example of this is the formation of dew on surfaces overnight. During the day, the temperature is warmer than it is at night, and the air has a relatively high holding capacity for water vapor. When the sun sets, the air cools, decreasing its capacity to hold water vapor. That extra water must go somewhere, and it does that by accumulating on surfaces. Similarly, when warm and cool air fronts collide, the chances for rain and thunderstorms increase. Furthermore, an increase in temperature enhances evaporation occurring at the Earth’s surface. This increased evaporation leads to greater concentrations of water vapor in the atmosphere which can lead to increased precipitation.

The change in temperature that we have already seen in the Earth’s average atmospheric temperature is relatively small (about 0.6 °C, according to Figure 7.5.2 from section 7.5). However, as with many of the aspects of climate change, the potential for greater changes increases dramatically as time progresses in the future. This can be seen in Figure 9.8.1, which displays a model of the predicted temperature increase. Notice that these changes occur relatively rapidly, and are not uniform across the globe. What might be some of the reasons for this?

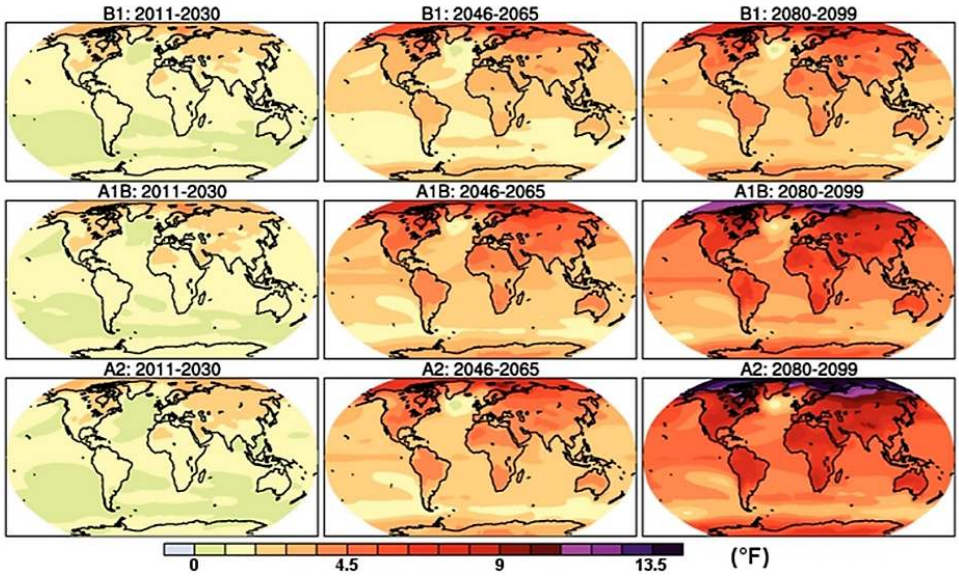


Figure 9.8.1: Projected changes in global average temperatures under three emissions scenarios (rows) for three different time periods (columns). Changes in temperatures are relative to 1961- 1990 averages. The scenarios come from the IPCC Special Report on Emissions Scenarios: B1 is a low emissions scenario, A1B is a medium-high emissions scenario, and A2 is a high emissions scenario. Source: IPCC Working Group I: The Physical Science Basis, 2007.

Changes in precipitation occur due to a variety of factors, including changes in atmospheric water vapor content due to changing temperature, as discussed above. Also at play is the heightened **evaporation** rate of water on Earth's surface under warmer temperatures. More evaporation leads to more precipitation. Finally, shifts in wind patterns impact the distribution of precipitation events. As you can see in Figure 9.8.2, there are some areas of the globe that are expected to have an increase in precipitation, while others are expected to have a dramatic decrease. Some major population centers projected to have a moderate to severe precipitation increase include (population estimates of the metropolitan area given in parentheses): New York, United States (20.1 million); Bogotá, Colombia (12.1 m.); and Manila, Philippines (11.9 m.). What sort of challenges might these cities face in the future as they deal with this change in their climate?

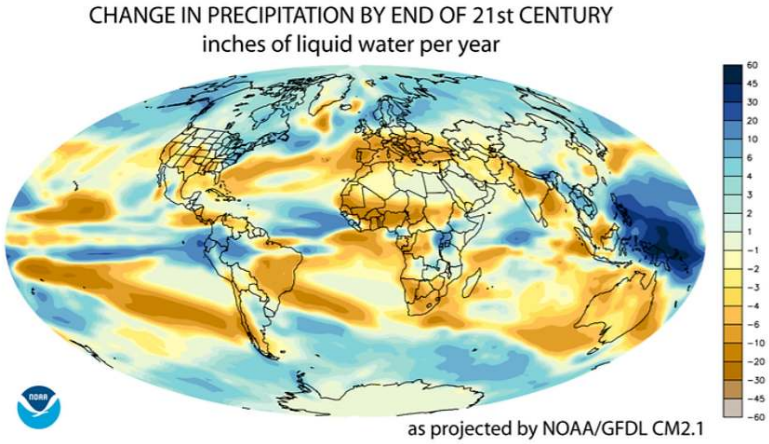


Figure 7.6.1). The plotted precipitation differences were computed as the difference between the 2081 to 2100 20-year averages minus the 1951 to 2000 50-year average. Blue areas project increases in precipitation; brown areas project decreases.

In contrast, many more major metropolitan areas are projected to have a moderate to severe precipitation decrease (droughts) by the end of the 21st century. These include Delhi, India (21.8 m.); Lagos, Nigeria (21 m.); São Paulo, Brazil (20.9 m.); Kolkata, India (14.6 m.); Istanbul, Turkey (14.4 m.); Los Angeles, United States (13.3 m.); Rio de Janeiro, Brazil (12 m.); Paris, France (12 m.); and Lahore, Pakistan (11.3 m.). The largest challenge that these areas are likely to face is a dwindling water supply for drinking and

agriculture. See Chapter 8 for more detail on challenges faced by societies to supply clean, reliable water to their populations and farms.

Additional challenges may be felt by all areas of the world with regard to changes in the seasonality or timing of precipitation, as well the form in which precipitation falls (e.g., mist or downpour; rain, ice, or snow). All of these factors affect the availability of soil water for plants, the flow of rivers and streams, and the overall accessibility of water worldwide. Furthermore, scientists predict an increase in the number and severity of storms as climate change progresses. For a full discussion of the potential impacts of this, see the assigned article.

Sea level rise While we know that water continuously cycles around the world (see Chapter 8 for information on the water cycle), and that the overall quantity of water on Earth will not change due to global climate change, the distribution of this water is changing. In particular, oceans are increasing in volume while land ice stores (such as **glaciers**) are decreasing. This contributes to an increase in sea level worldwide (Figure 9.8.3).

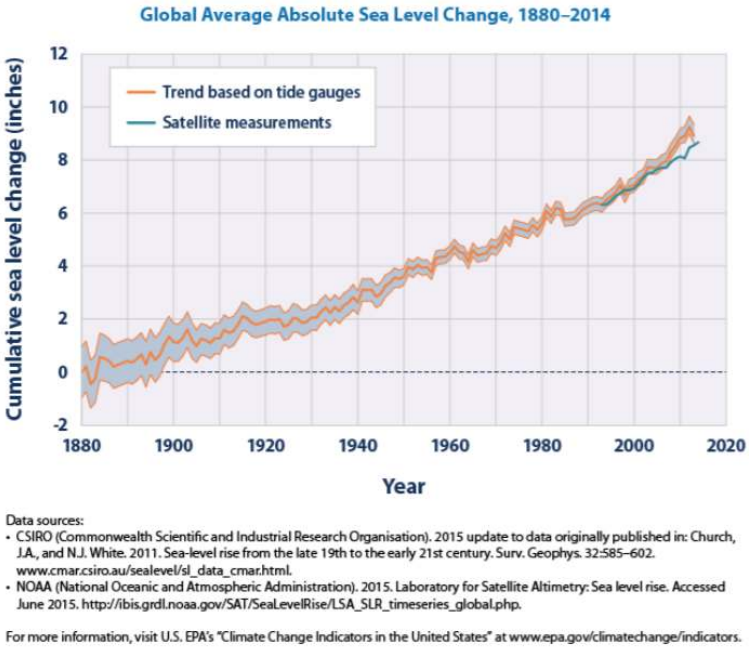


Figure 9.8.3: *This graph shows average absolute cumulative changes in sea level for the world's oceans since 1880, based on a combination of tide gauge measurements and recent satellite measurements. The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used.*

From the data in Figure 9.8.3, we see that sea level has increased at an average of 0.06 inches (0.15 cm) per year over the time period shown above. Most of this rise, however, has occurred within the most recent decades. The rate of increase has gone up to between 0.11 to 0.14 inches (0.28 to 0.36 cm) per year since 1993. There are two forces causing sea level to rise, both caused by climate change. First, the increased global temperature has caused increased ice melting in many regions of the globe. Melting **land ice** (such as the glacier shown in Figure 9.8.4) contributes to sea level rise because water that used to be stored in ice sitting on top of land becomes running water which reaches the ocean through **runoff.** We also observe **sea ice** melting (see http://www.epa.gov/climatechange/sci ence/indicators/index.html for data and figures). Sea ice, such as the ice that covers the arctic regions of the Northern Hemisphere, has no land underneath it. When it melts, the water stays in the same locations, and the overall sea level does not change.



Figure 9.8.4: Glacier Retreat

The second factor that influences sea level rise is a phenomenon called thermal expansion. Due to the physical properties of water, as water warms, its density decreases. A less dense substance will have fewer molecules in a given area than a more dense substance (see Chapter 1 supplemental material). This means that as the overall temperature of the oceans increases due to global climate change, the same amount of water molecules will now occupy a slightly larger volume. This may not seem significant, but considering the 1.3 billion trillion liters (264 billion gallons) of water in the ocean, even a small change in density can have large effects on sea level as a whole.

Scientists have already documented sea level rise in some areas of the world, including one familiar to most of us: the Southeastern United States. Figure 9.8.5 depicts the measured land area lost due to increasing sea level since 1996. Note that the Southeast (defined here as the Atlantic coast of North Carolina south to Florida) is particularly susceptible to land area loss due to the gently sloping nature of our coastline. Moving northward into the Mid-Atlantic States (defined here as Virginia north to Long Island, New York), coastal habitats tend to have a steeper geography, which protects against some losses.

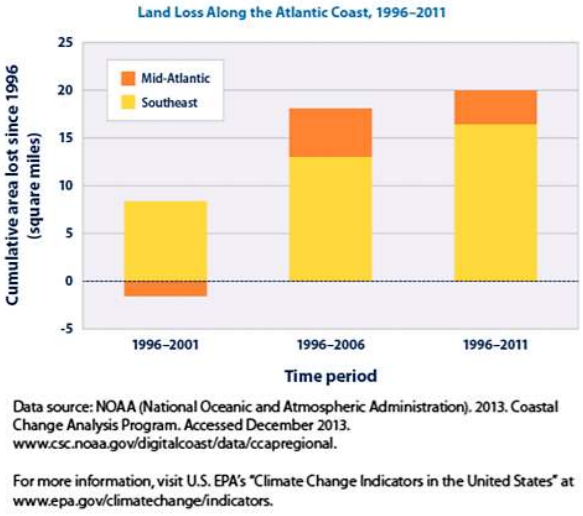


Figure 7.6.5: *This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011. The results are divided into two regions: the Southeast and the Mid-Atlantic. Negative numbers show where land loss is outpaced by the accumulation of new land.*

While the ecological effects of sea level rise remain in the United States, we don't project any catastrophic loss of life, property, or livelihood for some time. This is, in part, due to large investments that we have made in infrastructure to protect our cities and farmlands. This is not the case in many areas of the world. For a discussion of the impacts of sea level rise on less industrialized nations of Bangladesh, Maldives, Kiribati, and Fiji, review the required article reading.

Ocean acidification

Dissolved CO_2 is essential for many organisms, including shell-building animals and other organisms that form a hard coating on their exterior (e.g., shellfish, corals, Haptophyte algae). This hard coating is built out of aragonite, a mineral form of the molecule calcium carbonate, $CaCO_3$. These organisms rely on the formation of carbonate ions (see Chapter 1 supplemental material for information on ions), CO_3^{2-}, from dissolved CO_2, through a natural, chemical reaction that occurs. This takes place through a chain-reaction equation, where bicarbonate (HCO_3^-) is formed as an intermediate, and hydrogen ions (H^+) are generated (equations 9.8.1 and 9.8.2).

$$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \tag{9.8.1}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \tag{9.8.2}$$

To have a better visualization of this process, follow along with the interactive graphic at: http://www.whoi.edu/home/oceanus_ima...ification.html.

As you can see, both equations 9.8.1 and 9.8.2 each produce one H^+. This is significant to water chemistry because an increase in H+ concentration means a decrease in the pH of the water. You can see in Figure 9.8.6 that a lower pH means that the liquid is more acidic. As shown in the interactive graphic, an increase in CO_2 in the atmosphere causes additional CO_2 to be dissolved in the ocean. This means that more CO_2 in the atmosphere leads to more acidic ocean environments.

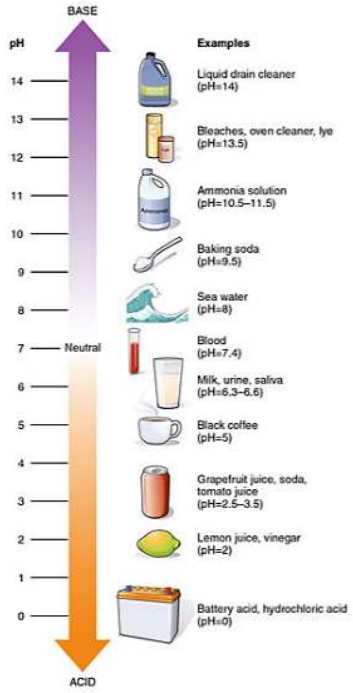


Figure 7.6.6: *The pH scale and relative acidity. Illustration from Anatomy & Physiology, Connexions Web site. http://cnx.org/content/col11496/1.6/, Jun 19, 2013.*

Unfortunately for shell-building animals, the buildup of H^+ in the more acidic ocean environment blocks the absorption of calcium and CO_3^{2-}, and makes the formation of aragonite more difficult. An aragonite deficit is already being documented in many of the world's oceans, as shown in Figure 9.8.7.

The increasing acidity of the world's oceans is resulting in habitat changes across the globe. This is only expected to worsen as atmospheric CO_2 levels continue to increase. Many organisms, including the corals that are the foundation species of the beautiful coral reefs, are very sensitive to changes in ocean pH. Scientists have documented cases of ecosystem destruction through coral bleaching, caused by the effects of climate change including ocean acidification and increased temperature. For more information, visit the NOAA Coral Reef Conservation Program website: coralreef.noaa.gov/threats/climate/.

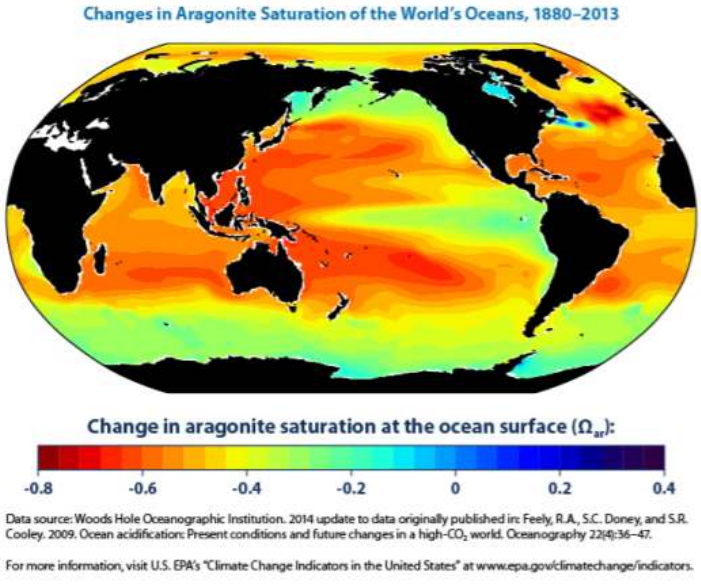


Figure 9.8.7: This map shows changes in the aragonite saturation level of ocean surface waters between the 1880s and the most recent decade (2004–2013). Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. A negative change represents a decrease in saturation.

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9.9: Tools Scientists Use to Study Climate Change

Scientists must gather together all data that is available to them in order to make meaningful conclusions and predictions regarding climate change. When they bring these data together, the prediction they make is in the form of a scientific **model.** A model is a projection of what might happen in the future based on knowledge of current and past events. The models that are published to predict climate change must pass a rigorous scientific peer-review process, and often require the combination of findings of hundreds of experiments. These large-scale models are typically beyond the capacity of a standard desktop computer, and must be run by large super-computers housed at research universities or government laboratories. For more information on how scientists build and test models, follow the link below and click on the slideshow animation, paying special attention to the sections "Model Overview" and "Testing Models." http://www.epa.gov/climatechange/science/future.html

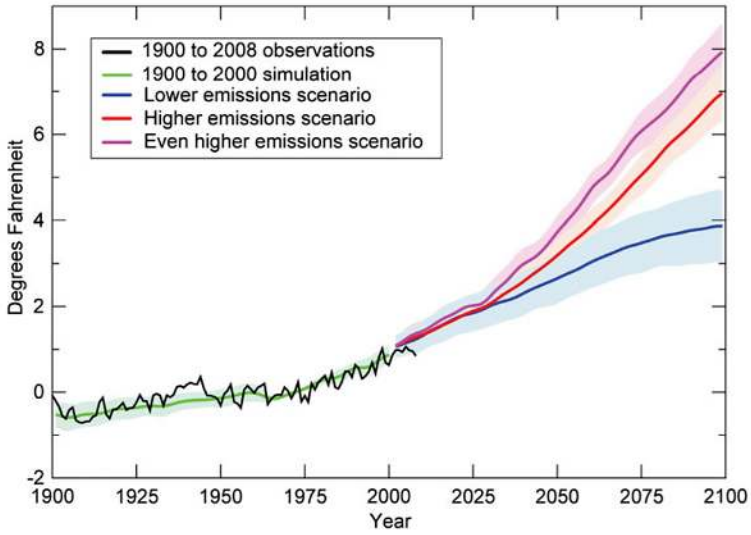


Figure 9.9.1: Observed and projected changes in global average temperature under three nopolicy emissions scenarios. The shaded areas show the likely ranges while the lines show the central projections from a set of climate models. A wider range of model types shows outcomes from 2 to 11.5°F. Changes are relative to the 1960-1979 average. Source: USGCRP 2009

Figure 9.9.1 is one example of a scientific model of the impacts of climate change. Within this figure, we see the directly-measured observations of global average temperature (black line). We also see models of four different scenarios: 1900 to 2000 simulation using actual greenhouse emissions (green line), and 2000 to 2100 simulation using very high (purple line), high (red line), and low (blue line) greenhouse gas emissions scenarios.

Why did scientists make a model of the data from 1900 to 2000 in Figure 9.9.1 when they could just look up the data in published literature? This is an important component of model testing. In order to ensure accuracy of the model, you should not only be able to predict future events, but past events as well. Scientists use this as a way to "calibrate" their model. Since this model reliably predicts past events, chances are good that it will reliably predict future events as well.

Another example of a climate model is shown in Figure 9.9.2 this time comparing climate projections with and without the influences of humans on greenhouse gas emissions. This large model is a combination of the work of many different models, in order to achieve the most accurate outcome.

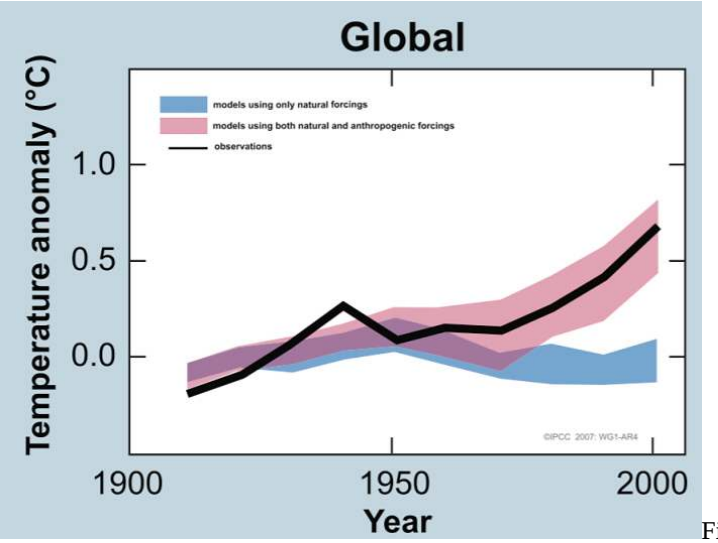


Figure 9.9.2: Comparison between observed average global temperatures and corresponding modeled temperatures with and without anthropogenic climate forces (IPCC, Working group 1, 2007).

In Figure 9.9.2, the decadal averages of observations are shown for the period 1906 to 2005 (black line). All temperatures are plotted relative to zero being defined as the corresponding average for the period from 1901 to 1950. The blue shaded band shows the 5% to 95% confidence interval for 19 simulations from 5 climate models using only the natural forcing effects due to solar activity and volcanoes. The red shaded band shows the 5% to 95% confidence interval for 58 different simulations from 14 climate models using both natural and anthropogenic forces. These different simulations and the different models are used by different scientific groups and represent different treatments of the Earth's systems. It is thus quite encouraging that model calculations are in major agreement with the assumption that global temperature change from 1900 to 2000 is due to both natural and anthropogenic effects, with anthropogenic effects being the major causes in its recent dramatic increase. You will see more examples of climate models as you make your way into the final section of the climate change chapter: consequences of climate change.

Resources

NASA Global Climate Change: Vital Signs of the Planet http://climate.nasa.gov/

NOAA Paleoclimatology: Astronomical Theory of Climate Change www.ncdc.noaa.gov/paleo/milankovitch.html

Sass, Ronald. Q2: What are the Causes of Global Climate Change? OpenStax CNX. Sep 22, 2009 http://cnx.org/contents/5d263a29-7bd...c233619bca33@3

University of San Diego Virtual Museum: Climate Change earthguide.ucsd.edu/virtualmu...ge2/01_1.shtml

US EPA: Future Climate Change http://www.epa.gov/climatechange/science/future.html

US EPA: Overview of Greenhouse Gases http://epa.gov/climatechange/ghgemissions/gases.html

Terms list

Albedo

Chlorofluorocarbon

Confidence interval

Fluorinated gases

Global warming potential

Greenhouse effect

Hydrofluorocarbon

Ice age

Ice core

Landfill

Milankovitch cycles

Model

Parts per million

Perfluorocarbon

Solar radiation

Stable isotopes

Sulfur hexafluoride

Thermal equilibrium temperature

Water vapor

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CHAPTER OVERVIEW

10: Air Pollution

10.1: Composition and Structure of the Atmosphere
10.2: Atmospheric Pollution
10.3: Outdoor Air Pollution
10.4: Indoor Air Pollution
10.5: Ozone Depletion
10.6: Acid Rain
10.7: Effects of Air Pollution on Human Health
10.8: Air Pollution Legislation
10.9: Chapter Resources

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10.1: Composition and Structure of the Atmosphere

Learning Objectives

By the end of this chapter, students will be able to

- Describe the composition and structure of the atmosphere.
- Explain the importance of the ozone layer, its depletion, and specific steps taken to address it.
- Distinguish between indoor and outdoor air pollution and how these compare among industrialized and less industrialized countries
- Identify natural and anthropogenic sources of air pollution
- Explain the effects of air pollution on human and ecosystem health
- Explain how the Clean Air Act legislation works and describe its outcomes

Atmosphere refers to the layer of gases that surrounds Earth and is held in place by Earth's gravitational attraction (gravity). The mix of gases in the atmosphere forms a complex system organized into layers that together support life on Earth. Although there are numerous gases, as shown in Table 10.1.1, the top four gases make up 99.998 % of the volume of *clean dry air* (unpolluted air that does not contain water vapor). Of this dry composition of the atmosphere **nitrogen**, by far, is the most common (78%).



Figure 10.1.1: Emissions from this power plant in New Mexico contained excessive amounts of sulfur dioxide. Image from National Parks Service (Public Domain).

Nitrogen dilutes oxygen and prevents rapid or instantaneous burning at the Earth's surface, as oxygen gas is a necessary reactant of the combustion process. Nitrogen is also needed and used by living things to make proteins, though as nitrogen gas, N_2, it is unavailable to most living things. **Oxygen** is used by all living things to make molecules that are essential for life. It is also essential for aerobic respiration as well as combustion or burning. **Argon** is a non-reactive gas and we use it in light bulbs, in double-pane windows, and to preserve priceless documents such as the original Declaration of Independence and the Constitution. **Carbon dioxide** is an essential gas used by plants and other organisms to make sugar (food) through photosynthesis. This process is essential for other life as well because during photosynthesis, water molecules are split apart and their oxygen is released back to the atmosphere. Carbon dioxide also acts as a blanket that prevents the escape of heat into outer space (see more on this in Chapter 7). The atmosphere is rarely, if ever, completely dry. **Water vapor** (water in a 'gas' state) is usually present up to about 4% of the total volume depending on location. In the Earth's desert regions (30° N/S) when dry winds are blowing, the water vapor contribution to the composition of the atmosphere will be near zero.

Table 10.1.1: Average composition of clean dry air in the lower atmosphere

Gas	Symbol	Content
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
Argon	Ar	0.93%
Carbon	CO_2	0.03% (this and the above three add to 99.998%)
Neon	Ne	18.20 parts per million
Helium	He	5.20 ppm
Krypton	Kr	1.10 ppm
Sulfur Dioxide	SO_2	1.00 ppm
Methane	CH_4	2.00 ppm
Hydrogen	H_2	0.50 ppm
Nitrous Oxide	N_2O	0.50 ppm
Xenon	Xe	0.09 ppm
Ozone	O_3	0.07 ppm
Nitrogen Dioxide	NO_2	0.02 ppm
Iodine	I_2	0.01 ppm
Carbon Monoxide	CO	Trace
Ammonia	NH_3	Trace

Source: National Weather Service www.srh.noaa.gov/jetstream/at...tmos_intro.htm

Earth's atmosphere is divided into four distinct layers based on thermal characteristics (temperature changes), chemical composition, movement, and density (Figure 10.1.2). The **troposphere** is the lowest layer extending from the surface up to roughly 18 km above the surface depending on location (varies from as low as 6 km to as high as 20 km). There is continuous flow and swirling of air constantly through convection currents redistributing heat and moisture around the globe. This results in the short-lived and local patterns of temperature and moisture that we call **weather**. Because gravity holds most air molecules close to the Earth's surface, the troposphere is the densest of all layers, containing about 75% of the total mass of the atmosphere. The density of the gases in this layer decrease with height so the air becomes thinner. In response, the temperature in the troposphere also decreases with height. As one climbs higher, the temperature drops from an average around 17°C (62°F) at sea level to about -51°C (-60°F) at the tropopause, a sharp boundary at the top of the troposphere that limits mixing between the troposphere and the upper layers.

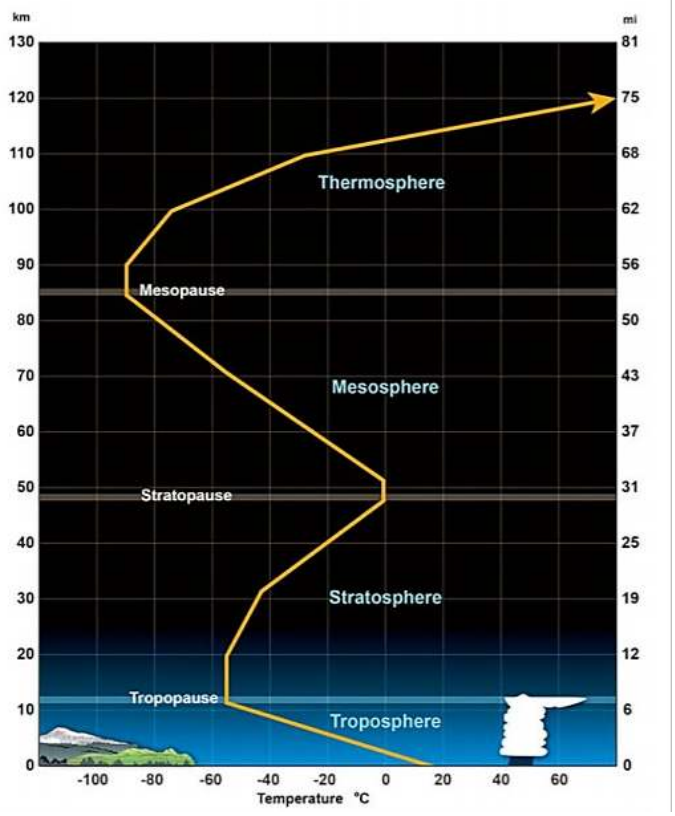


Figure 10.1.2: An average temperature profile through the lower layers of the atmosphere. Height (in miles and kilometers) is indicated along each side. Source: National Weather Service *www.srh.noaa.gov/jetstream/at...atmprofile.htm*

The **stratosphere** is the layer that extends from the tropopause up to about 50 km to 53 km above the Earth's surface depending on location. The proportions of most gases in this layer is similar to that of the troposphere with two main exceptions: 1) there is almost no water vapor in the stratosphere and 2) the stratosphere has nearly 1,000 times more ozone (O_3) than the troposphere. With only about 19% of the total mass of the atmosphere, the density of the stratosphere is significantly lower than the troposphere. However, temperature in this region increases with height as a result of heat that is produced during the formation of ozone (more on ozone in section 6.2). This heat is responsible for temperature increases from an average -51 °C (-60°F) at tropopause to a maximum of about -15°C (5°F) at the top of the stratosphere. This increase in temperature with height means warmer air is located above cooler air. This prevents "convection" as there is no upward vertical movement of the gases. The consequence of this little to no mixing of gases in the stratosphere makes it relatively calm but also means that once substances such as pollutants enter this zone, they can remain suspended for many years. The top of the stratosphere is bound by a boundary known as the **stratopause**.

Above the stratosphere is the **mesosphere** which extends to about 85 km above the Earth's surface. The mesosphere has no ozone molecules and the other gases such as oxygen and nitrogen continue to become less dense with height. As a result, not much ultraviolet and x-ray radiation from the sun is absorbed by molecules in this layer so temperature decreases with altitude. Both the stratosphere and the mesosphere are considered the middle atmosphere.

Between about 85 km and 600 km lies the **thermosphere**. This layer is known as the upper atmosphere. Unlike the mesosphere, the gases in this layer readily absorb incoming high energy ultraviolet and x-ray radiation from the sun. Because of this absorption, the temperature in the thermosphere increases with height and can reach as high as 2,000°C (3,600°F) near the top depending on solar activity. However, despite the high temperature, this layer of the atmosphere would still feel very cold to our skin due to the very thin atmosphere. The high temperature indicates the amount of energy absorbed by molecules but with so few in this layer, the total number of molecules is not enough to heat our skin. There's no sharp boundary that marks the end of the atmosphere. Pressure and density simply continue to decrease with distance until they become indistinguishable from the near-vacuum of outer space.

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10.2: Atmospheric Pollution

Air pollution occurs in many forms but can generally be thought of as gaseous and particulate contaminants that are present in the earth's atmosphere. Chemicals discharged into the air that have a direct impact on the environment are called **primary pollutants**. These primary pollutants sometimes react with other chemicals in the air to produce **secondary pollutants**.

Air pollution is typically separated into two categories: outdoor air pollution and indoor air pollution. **Outdoor air pollution** involves exposures that take place outside of the built environment. Examples include fine particles produced by the burning of coal, noxious gases such as sulfur dioxide, nitrogen oxides and carbon monoxide; ground-level ozone and tobacco smoke. **Indoor air pollution** involves exposures to particulates, carbon oxides, and other pollutants carried by indoor air or dust. Examples include household products and chemicals, out-gassing of building materials, allergens (cockroach and mouse dropping, mold, pollen), and tobacco smoke.

Sources of Air Pollution

A **stationary source** of air pollution refers to an emission source that does not move, also known as a point source. Stationary sources include factories, power plants, and dry cleaners. The term **area source** is used to describe many small sources of air pollution located together whose individual emissions may be below thresholds of concern, but whose collective emissions can be significant. Residential wood burners are a good example of a small source, but when combined with many other small sources, they can contribute to local and regional air pollution levels. Area sources can also be thought of as non-point sources, such as construction of housing developments, dry lake beds, and landfills.

A **mobile source** of air pollution refers to a source that is capable of moving under its own power. In general, mobile sources imply "on-road" transportation, which includes vehicles such as cars, sport utility vehicles, and buses. In addition, there is also a "non-road" or "off-road" category that includes gas-powered lawn tools and mowers, farm and construction equipment, recreational vehicles, boats, planes, and trains.

Agricultural sources arise from operations that raise animals and grow crops, which can generate emissions of gases and particulate matter. For example, animals confined to a barn or restricted area produce large amounts of manure. Manure emits various gases, particularly ammonia into the air. This ammonia can be emitted from the animal houses, manure storage areas, or from the land after the manure is applied. In crop production, the misapplication of fertilizers, herbicides, and pesticides can potentially result in aerial drift of these materials and harm may be caused.

Unlike the above mentioned sources of air pollution, air pollution caused by **natural sources**is not caused by people or their activities. An erupting volcano emits particulate matter and gases, forest and prairie fires can emit large quantities of "pollutants", dust storms can create large amounts of particulate matter, and plants and trees naturally emit volatile organic compounds which can form aerosols that can cause a natural blue haze. Wild animals in their natural habitat are also considered natural sources of "pollution".

Six Common Air Pollutants

The most commonly found air pollutants are *particulate matter*, *ground-level ozone*, *carbon monoxide*, *sulfur oxides*, *nitrogen oxides*, and *lead*. These pollutants can harm health and the environment, and cause property damage. Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. The U.S. Environmental Protection Agency (EPA) regulates them by developing criteria based on considerations of human and environmental health.

1. **Ground-level ozone** is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC) in the presence of sunlight. Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NOx and VOC. Breathing ozone can trigger a variety of health problems, particularly for children, the elderly, and people of all ages who have lung diseases such as asthma. Ground level ozone can also have harmful effects on sensitive vegetation and ecosystems. (Ground-level ozone should not be confused with the ozone layer, which is high in the atmosphere and protects Earth from ultraviolet light; ground-level ozone provides no such protection).
2. **Particulate matter**, also known as particle pollution, is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals,

metals, and soil or dust particles. The size of particles is directly linked to their potential for causing health problems. EPA is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects.

3. **Carbon monoxide** (CO) is a colorless, odorless gas emitted from combustion processes. Nationally and, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.
4. **Nitrogen dioxide** (NO_2) is one of a group of highly reactive gasses known as "oxides of nitrogen," or nitrogen oxides (NOx). Other nitrogen oxides include nitrous acid and nitric acid. EPA's National Ambient Air Quality Standard uses NO_2 as the indicator for the larger group of nitrogen oxides. NO2 forms quickly from emissions from cars, trucks and buses, power plants, and off-road equipment. In addition to contributing to the formation of ground-level ozone, and fine particle pollution, NO2 is linked with a number of adverse effects on the respiratory system.
5. **Sulfur dioxide** (SO_2) is one of a group of highly reactive gasses known as "oxides of sulfur." The largest sources of SO_2 emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO_2 emissions include industrial processes such as extracting metal from ore, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment. SO_2 is linked with a number of adverse effects on the respiratory system.
6. **Lead** is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from fuels in on-road motor vehicles (such as cars and trucks) and industrial sources. As a result of regulatory efforts in the U.S. to remove lead from on-road motor vehicle gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent between 1980 and 1999. Today, the highest levels of lead in air are usually found near lead smelters. The major sources of lead emissions to the air today are ore and metals processing and piston-engine aircraft operating on leaded aviation gasoline.

Indoor Air Pollution (Major concerns in developed countries)

Most people spend approximately 90 percent of their time indoors. However, the indoor air we breathe in homes and other buildings can be more polluted than outdoor air and can increase the risk of illness. There are many sources of indoor air pollution in homes. They include biological contaminants such as bacteria, molds and pollen, burning of fuels and environmental tobacco smoke, building materials and furnishings, household products, central heating and cooling systems, and outdoor sources. Outdoor air pollution can enter buildings and become a source of indoor air pollution.

Sick building syndrome is a term used to describe situations in which building occupants have health symptoms that are associated only with spending time in that building. Causes of sick building syndrome are believed to include inadequate ventilation, indoor air pollution, and biological contaminants. Usually indoor air quality problems only cause discomfort. Most people feel better as soon as they remove the source of the pollution. Making sure that your building is well-ventilated and getting rid of pollutants can improve the quality of your indoor air.

Secondhand Smoke (Environmental Tobacco Smoke)

Secondhand smoke is the combination of smoke that comes from a cigarette and smoke breathed out by a smoker. When a non-smoker is around someone smoking, they breathe in secondhand smoke.

Secondhand smoke is dangerous to anyone who breathes it in. There is no safe amount of secondhand smoke. It contains over 7,000 harmful chemicals, at least 250 of which are known to damage human health. It can also stay in the air for several hours after somebody smokes. Even breathing secondhand smoke for a short amount of time can hurt your body.

Over time, secondhand smoke can cause serious health issues in non-smokers. The only way to fully protect non-smokers from the dangers of secondhand smoke is to not allow smoking indoors. Separating smokers from nonsmokers (like "no smoking" sections in restaurants), cleaning the air, and airing out buildings does not completely get rid of secondhand smoke.

Source: Smokefree.gov

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10.3: Outdoor Air Pollution

Air pollution refers to the introduction, into the atmosphere, of substances that have harmful effects on humans, other living organisms, and the environment either as solid particles, liquid droplets or gases. Air pollution can result from natural processes such as dust storms, forest fires, and volcanic eruptions, or from human activities such as biomass burning, vehicular emissions, mining, agriculture, and industrial processes. Improved technology and government policies have helped reduce most types of outdoor air pollution in many industrialized countries including the United States, in recent decades. However, outdoor air quality is still a problem in less industrialized nations, especially in megacities of rapidly industrializing nations such as China and India.

Outdoor pollutants can come from **stationary (point)** sources or **mobile (nonpoint)** sources (Figure 10.3.1). Stationary sources have a fixed location, for example power plant smokestacks, burning, construction sites, farmlands and surface mines among others. Mobile sources of air pollutants move from place to place while emitting pollutants. Examples of mobile sources include vehicles, aircrafts, ships, and trains.

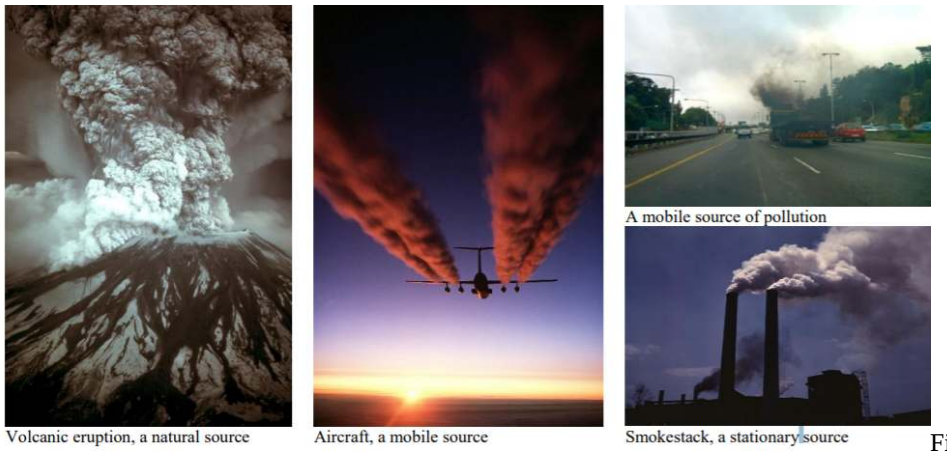


Figure 10.3.1: Images showing various sources of air pollution, including natural and anthropogenic, stationary and mobile. Source: All images obtained from Wiki Commons commons.wikimedia.org/wiki/Air_pollution

Pollutants are categorized into two major types based on how they originated namely primary and secondary pollutants. **Primary pollutants** are those released directly from the source into the air in a harmful form. The primary pollutants that account for nearly all air pollution problems are carbon monoxide (58%), volatile organic compounds (VOCs, 11%), nitrogen oxides (15%), sulfur dioxides (13%), and particulate material (3%). **Secondary pollutants** are produced through reactions between primary pollutants and normal atmospheric compounds. For example, ground-level ozone forms over urban areas through reactions, powered by sunlight, between primary pollutants (oxides of nitrogen) and other atmospheric gases such as VOCs.

6.3.1: Criteria pollutants

Under the Clean Air Act (section 6.7.1), the Environmental Protection Agency (EPA) establishes air quality standards to protect public health and the environment. EPA has set national air quality standards for six common air pollutants namely: 1) carbon monoxide; 2) ground-level ozone; 3) nitrogen dioxide; 4) Sulfur dioxide; 5) lead; and 6) particulate matter (also known as particle pollution). Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. EPA calls these pollutants "criteria" air pollutants because it regulates them by developing human health-based and/or environmentally-based criteria (science-based guidelines) for setting permissible levels. The set of limits based on human health is called primary standards. Another set of limits intended to prevent environmental and property damage is called secondary standards.

1. **Carbon Monoxide (CO)**: is a colorless, odorless gas emitted from combustion processes, specifically, the incomplete combustion of fuel. Nationally and, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.
2. **Ground-level ozone (O_3)**: is a colorless gas with a slightly sweet odor that is not emitted directly into the air, but is created by the interaction of sunlight, heat, oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). Ozone is likely to reach

unhealthy levels on hot sunny days in urban environments. Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NO_x and VOCs.

3. **Nitrogen dioxide (NO_2)**: is one of a group of highly reactive gasses known as "oxides of nitrogen," or "nitrogen oxides (NO_x)." Other nitrogen oxides include nitrous acid and nitric acid. NO_2 is a yellowish-brown to reddish-brown foul-smelling gas that is a major contributor to smog and acid rain. Nitrogen oxides result when atmospheric nitrogen and oxygen react at the high temperatures created by combustion engines. Most emissions in the U.S. result from combustion in vehicle engines, electrical utility, and industrial combustion.
4. **Sulfur dioxide (SO_2)**: Sulfur dioxide is one of a group of highly reactive gasses known as “oxides of sulfur.” The largest sources of SO_2 emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO_2emissions include industrial processes such as extracting metals from their ores, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment.
5. **Lead (Pb)**: is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from fuels in motor vehicles (such as cars and trucks) and industrial sources. As a result of EPA's regulatory efforts to remove lead from gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent during that time period. The major sources of lead emissions today are ore and metal processing and piston-engine aircraft operating on leaded aviation gasoline. Today, the highest levels of lead in air are usually found near lead smelters.
6. **Particulate material (PM)**, sometimes known simply as “**particulates**” refers to solid particles and liquid droplets suspended in the air we breathe. Particulate pollution is made up of a variety of components, including acids (nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (pollen and mold spores). The size of the particles in directly linked to their potential for causing health problems. Particles that are 10 micrometers in diameter or smaller generally pass through the throat and nose and enter the lungs. EPA groups these into two types: "**inhalable coarse particles**," with diameters larger than 2.5 micrometers and smaller than 10 micrometers and "**fine particles**," with diameters that are 2.5 micrometers and smaller. How small is 2.5 micrometers? Think about a single hair from your head. The average human hair is about 70 micrometers in diameter – making it 30 times larger than the largest fine particle (Figure 10.3.2). Our respiratory systems are equipped to filter larger particles out of the air once it is inhaled. However, the lungs are vulnerable to both coarse particles (PM_{10}), and fine particles ($PM_{2.5}$). These can slip past the respiratory system's natural defenses and get deep into the lungs and some may even get into the bloodstream. Coarse particles come from road dust while fine particles come from combustion processes.

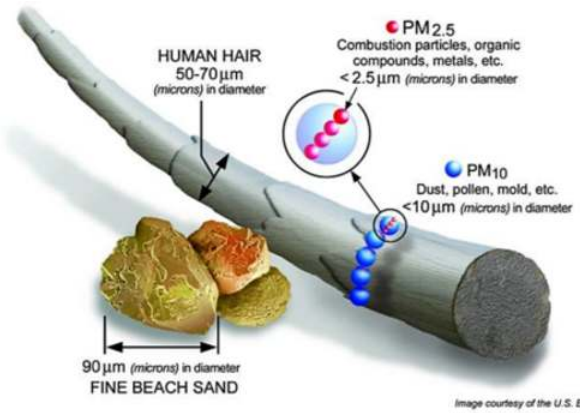


Figure 10.3.2: Graphic showing size comparison of particulate material (PM_{10} and $PM_{2.5}$) compared to fine beach sand and human hair. Source: US EPA www.epa.gov/air/particlepollution/basic.html

6.3.2: Volatile Organic Compounds

Volatile organic compounds (VOCs) are carbon-containing chemicals emitted as gases from natural and human-made sources. Natural sources of VOCs include plants, the largest source, and bacteria in the guts of termites and ruminant animals. These compounds are generally oxidized to carbon monoxide and carbon dioxide in the atmosphere. VOCs are of great concern because they are precursors for the formation of ozone, a secondary air pollutant.

A large number of synthetic organic chemicals such as benzene, toluene, formaldehyde, vinyl chloride, chloroform, and phenols are widely used as ingredients in countless household products. Paints, paint strippers, varnishes, many cleaning, disinfecting,

cosmetic, degreasing, and hobby products all contain VOCs. Fuels are also made up of organic chemicals. All of these products can release organic compounds while you are using them, and, to some degree, when they are stored. The “new car smell” characteristic of new cars is from a complex mix of dozens of VOC. Also, concentrations of many VOCs are consistently higher indoors (up to ten times higher) than outdoors. They are often held responsible for sick building syndrome, an illness resulting from indoor pollution in which the specific cause is not identified.

6.3.3: Smog

Smog is a mixture of air pollutants (sulfur dioxide, nitrogen oxides, ozone, and particulates) that often form over urban areas as a result of fossil fuel combustion. The term was coined from the terms “smoke” and “fog” referring to a brownish haze that pollutes the air, greatly reducing visibility and making it difficult for some people to breathe (Figure 10.3.3 and 10.3.4). There are two main types of smog: industrial and photochemical smog. **Industrial smog** is produced primarily by the burning of fossil fuels which produces carbon dioxide (from complete combustion), carbon monoxides (from partial combustion), sulfur, and mercury. The sulfur reacts with other chemicals in the atmosphere producing several sulfur compounds including sulfur dioxide. These compounds along with particulate material make up industrial smog. **Photochemical smog** is formed when sunlight drives chemical reactions between primary pollutants from automobiles and normal atmospheric compounds. The product is a mix of over 100 different chemicals with the most abundant being ground-level ozone.



Figure 10.3.3: Smog over Almaty city, Kazakhstan. Photo by Igors Jefimovs. Source: Wikicommons commons.wikimedia.org/wiki/C...dia/File:Smog_ over_Almaty.jpg



Figure 10.3.4: Smog over Santiago in Chile. Source: German Wikipedia commons.wikimedia.org/wiki/C...#/media/File:S antiago30std.jpg

6.3.4: Toxic pollutants

Toxic air pollutants, also known as hazardous air pollutants, are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects. Examples of toxic air pollutants include benzene, which is found in gasoline; perchloroethylene, which is emitted from some dry cleaning facilities; methylene chloride, which is used as a solvent and paint stripper by a number of industries; and others such as dioxin, asbestos, toluene, and metals such as cadmium, mercury, chromium, and lead compounds.

Most air toxics originate from human-made sources, including mobile sources (e.g., cars, trucks, buses) and stationary sources (e.g., factories, refineries, power plants), as well as indoor sources (e.g., some building materials and cleaning solvents). Some air

toxics are also released from natural sources such as volcanic eruptions and forest fires. Exposure to air toxics is mainly through breathing but some toxic air pollutants such as mercury can deposit onto soils or surface waters, where they are taken up by plants and ingested by animals and are eventually magnified up through the food chain. Like humans, animals may experience health problems if exposed to sufficiently high quantities of air toxics over time.

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10.4: Indoor Air Pollution

In both developed and developing nations, indoor air pollution poses a greater health risk than outdoor air pollution. According to the World Health Organization (WHO) and other agencies such as the Environmental Protection Agency (EPA), indoor air generally contains higher concentrations of toxic pollutants than outdoor air. Additionally, people generally spend more time indoors than outdoors, hence, the health effects from indoor air pollution in workplaces, schools, and homes are far greater than outdoor. Indoor pollution sources that release gases or particles into the air are the primary cause of indoor air quality problems in homes. Inadequate ventilation can increase indoor pollutant levels by not bringing in enough outdoor air to dilute emissions from indoor sources and by not carrying indoor air pollutants out of the home.

Outdoor air enters and leaves a building by infiltration, natural ventilation, and mechanical ventilation. In infiltration, outdoor air flows into the house through openings, joints, and cracks in walls, floors, and ceilings, and around windows and doors. In natural ventilation, air moves through opened windows and doors. Air movement associated with infiltration and natural ventilation is caused by air temperature differences between indoors and outdoors and by wind. Finally, there are a number of mechanical ventilation devices, from outdoor-vented fans that intermittently remove air from a single room, such as bathrooms and kitchen, to air handling systems that use fans and duct work to continuously remove indoor air and distribute filtered and conditioned outdoor air to strategic points throughout the house. The rate at which outdoor air replaces indoor air is described as the air exchange rate. When there is little infiltration, natural ventilation, or mechanical ventilation, the air exchange rate is low and pollutant levels can increase. High temperature and humidity levels can also increase concentrations of some pollutants.

There are many sources of indoor air pollution in any home (Figure 10.4.1). These include combustion sources such as oil, gas, kerosene, coal, wood, and tobacco products; building materials and furnishings as diverse as deteriorated, asbestos-containing insulation, wet or damp carpet, and cabinetry or furniture made of certain pressed wood products; products for household cleaning and maintenance, personal care, or hobbies; central heating and cooling systems and humidification devices. Pollutants causing indoor air pollution can also originate from outside sources such as radon, pesticides, and outdoor air pollution. Radon is a naturally occurring radioactive gas produced from the decay of uranium in rock. If a building/home is constructed in an area with uranium containing rock, the gas can seep through the foundations and accumulate in basements. Exposure to radon can cause lung cancer.

The relative importance of any single source depends on how much of a given pollutant it emits and how hazardous those emissions are. In some cases, factors such as how old the source is and whether it is properly maintained are significant. For example, an improperly adjusted gas stove can emit significantly more carbon monoxide than one that is properly adjusted. Some sources, such as building materials, furnishings, and household products like air fresheners, release pollutants more or less continuously. Other sources, related to activities carried out in the home, release pollutants intermittently. These include smoking, the use of unvented or malfunctioning stoves, furnaces, or space heaters, the use of solvents in cleaning and hobby activities, the use of paint strippers in redecorating activities, and the use of cleaning products and pesticides in house-keeping. High pollutant concentrations can remain in the air for long periods after some of these activities.

Risks from indoor air pollution differ between less industrialized and industrialized nations. Indoor pollution has a greater impact in less industrialized nations where many people use cheaper sources of fuel such as wood, charcoal, and crop waste among others for cooking and heating, often with little or no ventilation. The most significant indoor pollutant, therefore, is soot and carbon monoxide. In industrialized nations, the primary indoor air health risks are cigarette smoke and radon.

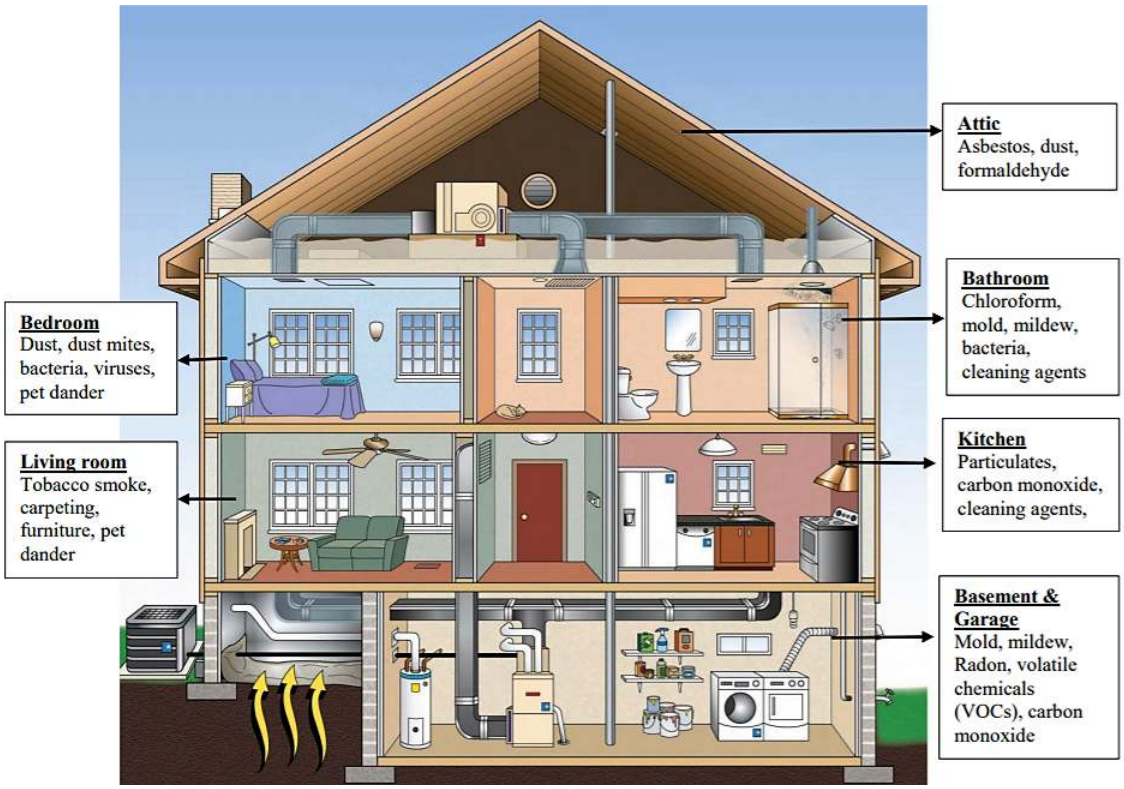


Figure 10.4.1: Sources of indoor air pollution. Image source: EPA http://www.epa.gov/iaq/pdfs/careforyourair.pdf

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10.5: Ozone Depletion

Ozone (O_3)

Ozone is an important molecule in many ways. As we have seen, ozone in the lower atmosphere can cause a number of different air pollution problems and health effects. However, in the upper atmosphere, is it one of the primary ways that UV light is blocked from reaching the surface of the Earth. The "ozone layer" is a shield (or maybe like sunglasses for the Earth, protecting us from harmful levels of UV radiation. Chemicals released on the ground by human manufacturing and industry move up into the upper atmosphere and damage this protective ozone layer. The ozone depletion process begins when **CFCs** (chlorofluorocarbons) and other ozone-depleting substances (ODS) are emitted into the atmosphere. CFC molecules are extremely stable, and they do not dissolve in rain. After a period of several years, ODS molecules reach the stratosphere, about 10 kilometers above the Earth's surface. CFCs were used by industry as refrigerants, degreasing solvents, and propellants.

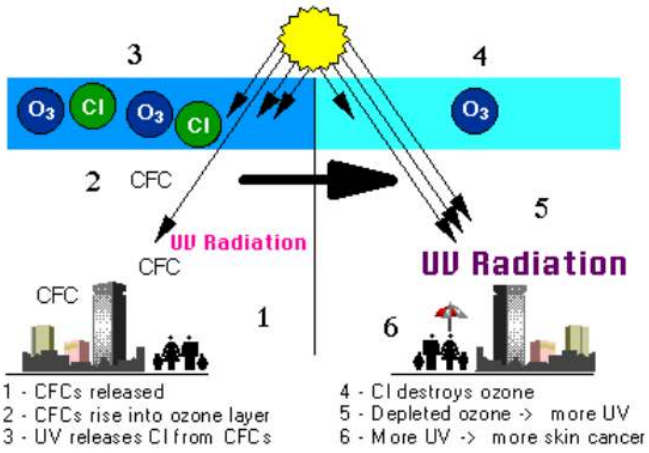


Figure 10.5.1. Strong UV light breaks apart the ODS molecule. CFCs, HCFCs, carbon tetrachloride, methyl chloroform, and other gases release chlorine atoms, and halons and methyl bromide release bromine atoms. It is these atoms that actually destroy ozone, not the intact ODS molecule. It is estimated that one chlorine atom can destroy over 100,000 ozone molecules before it is removed from the stratosphere. Credit: NASA GSFC.

Ozone (O_3) is constantly produced and destroyed in a natural cycle, as shown in Figure 10.5.1. However, the overall amount of ozone is essentially stable. This balance can be thought of as a stream's depth at a particular location. Although individual water molecules are moving past the observer, the total depth remains constant. Similarly, while ozone production and destruction are balanced, ozone levels remain stable. This was the situation until the past several decades. Large increases in stratospheric ODS, however, have upset that balance. In effect, they are removing ozone faster than natural ozone creation reactions can keep up. Therefore, ozone levels fall.

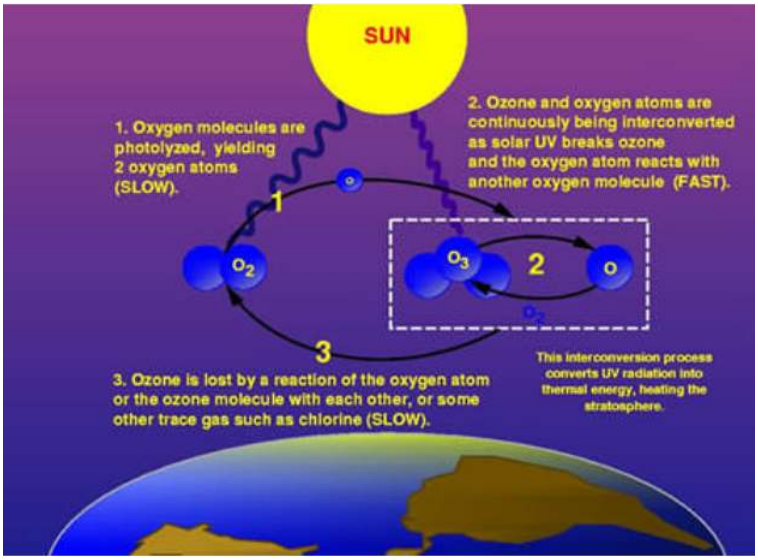


Figure 10.5.2. Because ozone filters out harmful UVB radiation, less ozone means higher UVB levels at the surface. The more the depletion, the larger the increase in incoming UVB. UVB has been linked to skin cancer, cataracts, damage to materials like plastics, and harm to certain crops and marine organisms. Although some UVB reaches the surface even without ozone depletion, its harmful effects will increase as a result of this problem.

Policies to Reduce Ozone Destruction

One success story in reducing pollutants that harm the atmosphere concerns ozone-destroying chemicals. In 1973, scientists calculated that CFCs could reach the stratosphere and break apart. This would release chlorine atoms, which would then destroy ozone. Based only on their calculations, the United States and most Scandinavian countries banned CFCs in spray cans in 1978. More confirmation that CFCs break down ozone was needed before more was done to reduce production of ozone-destroying chemicals. In 1985, members of the British Antarctic Survey reported that a 50% reduction in the ozone layer had been found over Antarctica in the previous three springs.

Two years after the British Antarctic Survey report, the “Montreal Protocol on Substances that Deplete the Ozone Layer” was ratified by nations all over the world. The **Montreal Protocol**controls the production and consumption of 96 chemicals that damage the ozone layer (Figure 10.5.3). CFCs have been mostly phased out since 1995, although they were used in developing nations until 2010. Some of the less hazardous substances will not be phased out until 2030. The Protocol also requires that wealthier nations donate money to develop technologies that will replace these chemicals.

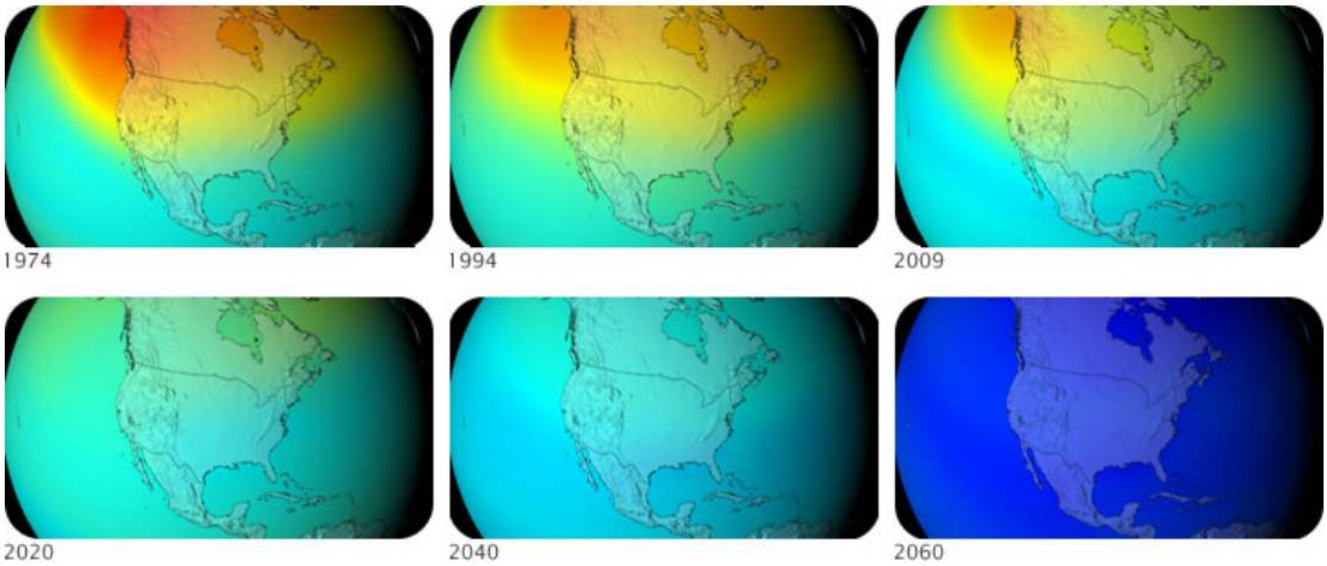


Figure 10.5.3. Ozone levels over North America decreased between 1974 and 2009. Models of the future predict what ozone levels would have been if CFCs were not being phased out. Warmer colors indicate more ozone.

Because CFCs take many years to reach the stratosphere and can survive there a long time before they break down, the ozone hole will probably continue to grow for some time before it begins to shrink. The ozone layer will reach the same levels it had before 1980 around 2068 and 1950 levels in one or two centuries.

Health and Environmental Effects of Ozone Layer Depletion

There are three types of UV light: UVA, UVB, and UVC. Reductions in stratospheric ozone levels will lead to higher levels of UVB reaching the Earth's surface. The sun's output of UVB does not change; rather, less ozone means less protection, and hence more UVB reaches the Earth. Studies have shown that in the Antarctic, the amount of UVB measured at the surface can double during the annual ozone hole.

Laboratory and epidemiological studies demonstrate that UVB causes non-melanoma skin cancers and plays a major role in malignant melanoma development. In addition, UVB has been linked to cataracts, a clouding of the eye's lens. All sunlight contains some UVB, even with normal stratospheric ozone levels. Therefore, it is always important to protect your skin and eyes from the sun. Ozone layer depletion increases the amount of UVB and the risk of health effects.

UVB is generally harmful to cells, and therefore all organisms. UVB cannot penetrate into an organism very far and thus tends to only impact skin cells. Microbes like bacteria, however, are composed of only one cell and can therefore be harmed by UVB,

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10.6: Acid Rain

Acid rain is a term referring to a mixture of wet and dry deposition (deposited material) from the atmosphere containing higher than normal amounts of nitric and sulfuric acids. The precursors, or chemical forerunners, of acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from fossil fuel combustion. Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. The result is a mild solution of sulfuric acid and nitric acid. When sulfur dioxide and nitrogen oxides are released from power plants and other sources, *prevailing winds* blow these compounds across state and national borders, sometimes over hundreds of miles.



Acid rain impacts on forests. "Smokey Mountain National Park - Acid Rain on Top" by NatureLifePhoto, CC BY-NC-ND 2.0

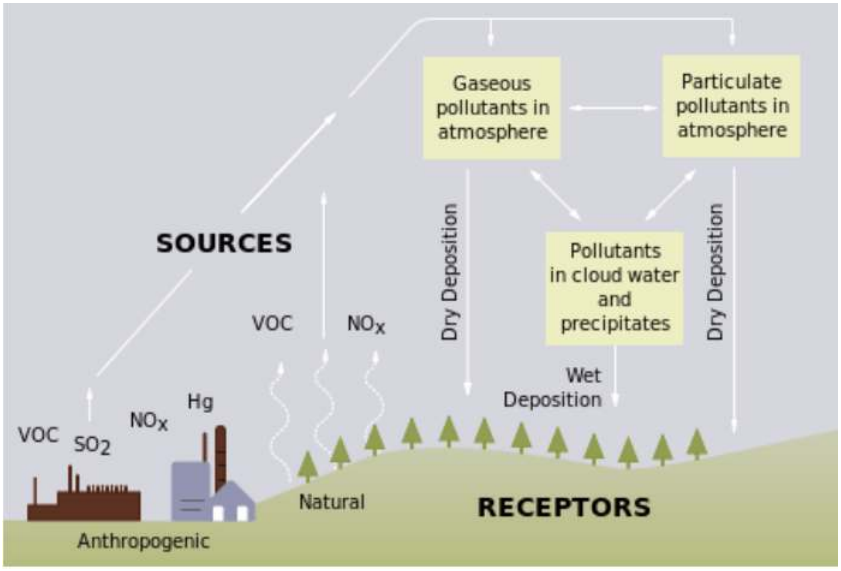


Figure 10.6.1. Processes involved in acid deposition.

Acid rain is measured using a scale called "pH." The lower a substance's pH, the more acidic it is. Pure water has a pH of 7.0. However, normal rain is slightly acidic because carbon dioxide (CO_2) dissolves into it forming weak carbonic acid, giving the

resulting mixture a pH of approximately 5.6 at typical atmospheric concentrations of CO_2. As of 2000, the most acidic rain falling in the U.S. has a pH of about 4.3.

Effects of Acid Rain

Acid rain causes **acidification** of lakes and streams and contributes to the damage of trees at high elevations (for example, red spruce trees above 2,000 feet) and many sensitive forest soils. In addition, acid rain accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of our nation's cultural heritage. Prior to falling to the earth, sulfur dioxide (SO_2) and nitrogen oxide (NO_x) gases and their particulate matter derivatives—sulfates and nitrates—contribute to visibility degradation and harm public health.

The **ecological** effects of acid rain are most clearly seen in the aquatic, or water, environments, such as streams, lakes, and marshes. Most lakes and streams have a pH between 6 and 8, although some lakes are naturally acidic even without the effects of acid rain. Acid rain primarily affects sensitive bodies of water, which are located in watersheds whose soils have a limited ability to neutralize acidic compounds (called "buffering capacity"). Lakes and streams become acidic (i.e., the pH value goes down) when the water itself and its surrounding soil cannot buffer the acid rain enough to neutralize it. In areas where buffering capacity is low, acid rain releases aluminum from soils into lakes and streams; aluminum is highly toxic to many species of aquatic organisms. Acid rain causes slower growth, injury, or death of **forests**. Of course, acid rain is not the only cause of such conditions. Other factors contribute to the overall stress of these areas, including air pollutants, insects, disease, drought, or very cold weather. In most cases, in fact, the impacts of acid rain on trees are due to the combined effects of acid rain and these other environmental stressors.



Figure 10.6.2. A gargoyle that has been damaged by acid rain.

Acid rain and the dry deposition of acidic particles contribute to the corrosion of **metals**(such as bronze) and the deterioration of paint and stone (such as marble and limestone). These effects significantly reduce the societal value of buildings, bridges, cultural objects (such as statues, monuments, and tombstones), and cars (Figure 10.6.2).

Sulfates and nitrates that form in the atmosphere from sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions contribute to **visibility impairment,** meaning we cannot see as far or as clearly through the air. The pollutants that cause acid rain—sulfur dioxide (SO_2) and nitrogen oxides (NO_x)—damage **human health**. These gases interact in the atmosphere to form fine sulfate and nitrate particles that can be transported long distances by winds and inhaled deep into people's lungs. Fine particles can also penetrate indoors. Many scientific studies have identified a relationship between elevated levels of fine particles and increased illness and premature death from heart and lung disorders, such as asthma and bronchitis.

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10.7: Effects of Air Pollution on Human Health

The World Health Organization (WHO) and other international agencies recognize air pollution as a major threat to human health. Numerous scientific studies have linked air pollution to a variety of health problems (Table 10.7.1) including: aggravation of respiratory and cardiovascular diseases; decreased lung function; increased frequency and severity of respiratory symptoms such as difficulty breathing and coughing; increased susceptibility to respiratory infections; effects on the nervous system, including the brain, such as IQ loss and impacts on learning, memory, and behavior; cancer; and premature death. Immediate effects of air pollution may show up after a single exposure or repeated exposures. Other health effects may show up either years after exposure has occurred or only after long or repeated periods of exposure.

Immediate effects of air pollution include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. Such immediate effects are usually short-term and treatable. Sometimes the treatment is simply eliminating the person's exposure to the source of the pollution, if it can be identified. Symptoms of some diseases, including asthma, hypersensitivity pneumonitis, and humidifier fever , may also show up soon after exposure to some indoor air pollutants.

Table 10.7.1: Sources and health effects of criteria pollutants

Pollutant	Sources	Health Effects
Ground-level Ozone (O_3)	Secondary pollutant typically formed by chemical reaction of volatile organic compounds (VOCs) and NO_x in the presence of sunlight.	Decreases lung function and causes respiratory symptoms, such as coughing and shortness of breath; aggravates asthma and other lung diseases leading to increased medication use, hospital admissions, emergency department (ED) visits, and premature mortality.
Particulate Matter (PM)	Emitted or formed through chemical reactions; fuel combustion (e.g., burning coal, wood, diesel); industrial processes; agriculture (plowing, field burning); and unpaved roads.	Short-term exposures can aggravate heart or lung diseases leading to respiratory symptoms, increased medication use, hospital admissions, ED visits, and premature mortality; long-term exposures can lead to the development of heart or lung disease and premature mortality.
Lead	Smelters (metal refineries) and other metal industries; combustion of leaded gasoline in piston engine aircraft; waste incinerators; and battery manufacturing.	Damages the developing nervous system, resulting in IQ loss and impacts on learning, memory, and behavior in children. Cardiovascular and renal effects in adults and early effects related to anemia.
Oxides of Nitrogen (NO_x)	Fuel combustion (e.g., electric utilities, industrial boilers, and vehicles) and wood burning.	Aggravate lung diseases leading to respiratory symptoms, hospital admissions, and ED visits; increased susceptibility to respiratory infection.
Carbon Monoxide (CO)	Fuel combustion (especially vehicles), industrial processes, fires, waste combustion, and residential wood burning.	Reduces the amount of oxygen reaching the body’s organs and tissues; aggravates heart disease, resulting in chest pain and other symptoms leading to hospital admissions and ED visits.
Sulfur Dioxide (SO_2)	Fuel combustion (especially high-sulfur coal); electric utilities and industrial processes; and natural sources such as volcanoes.	Aggravates asthma and increased respiratory symptoms. Contributes to particle formation with associated health effects.

Source: www.epa.gov

The likelihood of immediate reactions to air pollutants depends on several factors. Age and preexisting medical conditions are two important influences. Some sensitive individuals appear to be at greater risk for air pollution-related health effects, for example, those with pre-existing heart and lung diseases (e.g., heart failure/ischemic heart disease, asthma, emphysema, and chronic bronchitis), diabetics, older adults, and children. In other cases, whether a person reacts to a pollutant depends on individual sensitivity, which varies tremendously from person to person. Some people can become sensitized to biological pollutants after repeated exposures, and it appears that some people can become sensitized to chemical pollutants as well.

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10.8: Air Pollution Legislation

In 1930, 63 people died and 1000 were sickened in Belgium when a phenomenon referred to as temperature inversion caused pollutants to be trapped near the surface, leading to a sudden spike in atmospheric sulfur levels. In October 1948, a thick cloud of air pollution formed above the industrial town of Donora, Pennsylvania. The cloud which lingered for five days, killed 20 people and caused sickness in 6,000 of the town's 14,000 people. In 1952, the infamous London fog in which acid aerosols trapped in the lower atmosphere killed 4000 people. Events like these alerted us to the dangers that air pollution poses to public health.

6.7.1: Clean Air Act

In the United States, several federal and state laws were passed, including the original Clean Air Act of 1963, which established funding for the study and cleanup of air pollution. But there was no comprehensive federal response to address air pollution until Congress passed a much stronger Clean Air Act in 1970. That same year Congress created the Environmental Protection Agency (EPA) and gave it the primary role in carrying out the law. Since 1970, EPA has been responsible for a variety of Clean Air Act programs to reduce air pollution nationwide. The Clean Air Act is a federal law covering the entire country. However, states, tribes and local governments do a lot of the work to meet the Act's requirements. For example, representatives from these agencies work with companies to reduce air pollution. They also review and approve permit applications for industries or chemical processes.

6.7.2: EPA's Role

EPA's mission is basic health and environmental protection from air pollution for all Americans. To achieve this mission, EPA implements a variety of programs under the Clean Air Act that focus on:

- reducing outdoor, or ambient, concentrations of air pollutants that cause smog, haze, acid rain, and other problems;
- reducing emissions of toxic air pollutants that are known to, or are suspected of, causing cancer or other serious health effects; and
- phasing out production and use of chemicals that destroy stratospheric ozone.

Under the Clean Air Act, EPA sets limits on certain air pollutants, including setting limits on how much can be in the air anywhere in the United States. The Clean Air Act also gives EPA the authority to limit emissions of air pollutants coming from sources like chemical plants, utilities, and steel mills. Individual states or tribes may have stronger air pollution laws, but they may not have weaker pollution limits than those set by EPA. EPA must approve state, tribal, and local agency plans for reducing air pollution. If a plan does not meet the necessary requirements, EPA can issue sanctions against the state and, if necessary, take over enforcing the Clean Air Act in that area. EPA assists state, tribal, and local agencies by providing research, expert studies, engineering designs, and funding to support clean air progress. Since 1970, Congress and the EPA have provided several billion dollars to the states, local agencies, and tribal nations to accomplish this.

6.7.3: State and Local Governments' Role

It makes sense for state and local air pollution agencies to take the lead in carrying out the Clean Air Act. They are able to develop solutions for pollution problems that require special understanding of local industries, geography, housing, and travel patterns, as well as other factors. State, local, and tribal governments also monitor air quality, inspect facilities under their jurisdictions and enforce Clean Air Act regulations. States have to develop State Implementation Plans (SIPs) that outline how each state will control air pollution under the Clean Air Act. A SIP is a collection of the regulations, programs and policies that a state will use to clean up polluted areas. The states must involve the public and industries through hearings and opportunities to comment on the development of each state plan.

6.7.4: Outcomes of the Clean Air Act

For more than forty years, the Clean Air Act has cut pollution as the U.S. economy has grown. The combined emissions of the six criteria pollutants has continued to decrease while population, gross domestic product, energy consumption, and vehicle miles travelled have all continued to increase (Figure 6.7.1). The following is a summary of some of the accomplishments of the Clean Air Act:

- Clean Air Act programs have lowered levels of the six criteria pollutants - particulates, ozone, lead, carbon monoxide, nitrogen dioxide and sulfur dioxide - as well as numerous toxic pollutants.

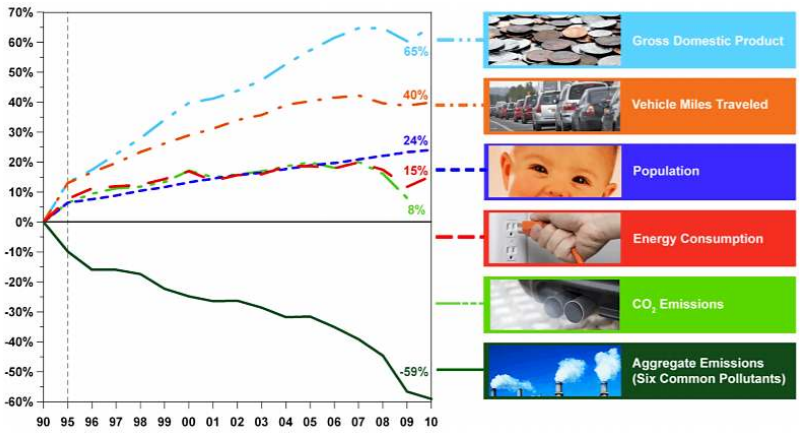


Figure 10.8.1: Showing a decrease in the combined emissions for the six criterial pollutants in the past two decades. Meanwhile, population, energy consumption, vehicle miles travelled, and gross domestic product have all increased. Source: US EPA

- From 1970 to 2012, aggregate national emissions of the six common pollutants alone dropped an average of 72 percent while gross domestic product grew by 219 percent (Figure 6.7.1). This progress reflects efforts by state, local and tribal governments; EPA; private sector companies; environmental groups and others.
- The emissions reductions have led to dramatic improvements in the quality of the air that we breathe.
- These air quality improvements have enabled many areas of the country to meet national air quality standards set to protect public health and the environment. For example, all of the 41 areas that had unhealthy levels of carbon monoxide in 1991 now have levels that meet the healthbased national air quality standard. A key reason is that the motor vehicle fleet is much cleaner because of Clean Air Act emissions standards for new motor vehicles.
- Airborne lead pollution, a widespread health concern before EPA phased out lead in motor vehicle gasoline under Clean Air Act authority, now meets national air quality standards in most areas of the country.

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10.9: Chapter Resources

Summary

Air pollution can be thought of as gaseous and particulate contaminants that are present in the earth's atmosphere. Chemicals discharged into the air that have a direct impact on the environment are called primary pollutants. These primary pollutants sometimes react with other chemicals in the air to produce secondary pollutants. The commonly found air pollutants, known as criteria pollutants, are particle pollution, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. These pollutants can harm health and the environment, and cause property damage. The historical record shows that the climate system varies naturally over a wide range of time scales. In general, climate changes prior to the Industrial Revolution in the 1700s can be explained by natural causes, such as changes in solar energy, volcanic eruptions, and natural changes in greenhouse gas concentrations. Recent climate changes, however, cannot be explained by natural causes alone. Natural causes are very unlikely to explain most observed warming, especially warming since the mid-20th century. Rather, human activities can explain most of that warming.

The primary human activity affecting the amount and rate of climate change is greenhouse gas emissions from the burning of fossil fuels. Greenhouse gas concentrations in the atmosphere will continue to increase unless the billions of tons of our annual emissions decrease substantially. Increased concentrations are expected to increase Earth's average temperature, influence the patterns and amounts of precipitation, reduce ice and snow cover, as well as permafrost, raise sea level and increase the acidity of the oceans. These changes will impact our food supply, water resources, infrastructure, ecosystems, and even our own health. Acid rain is a term referring to a mixture of wet and dry deposition from the atmosphere containing higher than normal amounts of nitric and sulfuric acids. The precursors of acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NOx) resulting from fossil fuel combustion. Acid rain causes acidification of lakes and streams, contributes to the damage of trees and many sensitive forest soils. In addition, acid rain accelerates the decay of building materials and paints, contributes to the corrosion of metals and damages human health. The ozone depletion process begins when CFCs and other ozone-depleting substances (ODS) are emitted into the atmosphere. Reductions in stratospheric ozone levels lead to higher levels of UVB reaching the Earth's surface. The sun's output of UVB does not change; rather, less ozone means less protection, and hence more UVB reaches the Earth. Ozone layer depletion increases the amount of UVB tat lead to negative health and environmental effects.

Review Questions

1. Ground-level ozone…
   A. Protects us from radiation
   B. Is a primary pollutant
   C. Is a secondary pollutant
   D. Reduces visibility but is mostly harmless to human health
   E. Is emitted from motor vehicles
2. Secondary pollutants are pollutants…
   A. Emitted from non-point sources
   B. That are created from the reaction of primary pollutants and other chemicals
   C. That are less hazardous than primary pollutants
   D. That have reduced ability to stay aloft in the atmosphere
   E. Emitted by Class 2 polluters
3. Depletion of the stratospheric ozone layer occurs when molecules of ozone are destroyed by chemicals such as…
   A. CFC
   B. DDT
   C. O_3
   D. PCB
   E. CH_4
4. What is the function of the stratospheric ozone layer?

A. Provides the biosphere with a source of elemental oxygen
B. Protects against ultraviolet light
C. Shields the Earth from high-energy cosmic rays
D. Protects organisms from infrared radiation
E. Creates UVB radiation for vitamin D synthesis

5. Anthropogenic causes of acid rain are primarily due to which one of the following?

A. Destruction of the ozone layer
B. Emissions of sulfur dioxide and nitrogen oxides from the combustion of fossil fuels
C. Emissions of carbon dioxide from the combustion of fossil fuels
D. Industrial emissions of acids
E. Acids formed in the contrails of airplanes

6. The scientific consensus regarding global climate change is that these changes are…

A. Caused by natural, Earth-based phenomena such as volcanoes
B. Poorly understood and no scientific conclusions can be made at this time
C. Primarily caused by human activities
D. Caused by eccentricity in Earth's orbit and by changes in solar intensity
E. No greater or different than changes seen in the medieval times

7. Greenhouse gases are known to raise air temperatures by…

A. absorbing infrared radiation
B. creating heat through chemical reactions with atmospheric pollutants
C. absorbing incoming visible light from the sun
D. trapping high energy molecules and atomic particles
E. releasing heat stored in high-altitude catalytic cycles

8. Changes in reflectivity of visible light affect how much energy enters Earth's system. What term is used by scientists to describe the reflectivity of a surface?

A. Contrastivity
B. Libido
C. Mirror-effect
D. Alluvium
E. Albedo

9. What is the primary cause of ocean acidification?

A. Atmospheric CO2 dissolving in ocean water
B. Increases in acid rain
C. Increased erosion of acid-containing rocks
D. Water draining into the ocean has a higher pH from industrial pollutants
E. All of the above

10. Which one of the following is not a predicted consequence of global climate change?

A. Spread of diseases carried by insects, such as malaria
B. Rise in sea levels
C. Increases in the global average air and ocean temperatures
D. Intensity of precipitation events will likely increase on average.
E. All of the above

See Appendix for answers

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CHAPTER OVERVIEW

11: Water Resources and Pollution

11.1: Water Cycle and Fresh Water Supply
11.2: Water Supply Problems and Solutions
11.3: Water Scarcity and Storage
11.4: Water Pollution
11.5: Water Treatment
11.6: Water Management
11.7: Case Study - The Aral Sea - Going, Going, Gone
11.8: Chapter Resources

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11.1: 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 11.1.1). 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.

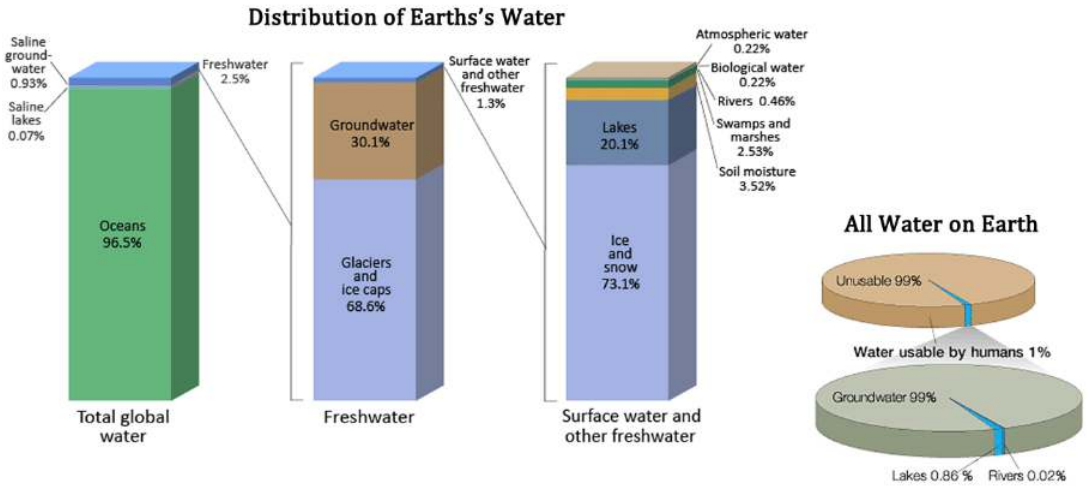


Figure 11.1.1. Earth's Water Reservoirs. Bar chart Distribution of Earth's water including total global water, fresh water, and surface water and other fresh water and Pie chart Water usable by humans and sources of usable water. Source: United States Geographical Survey Igor Skiklomanov's chapter "World 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).

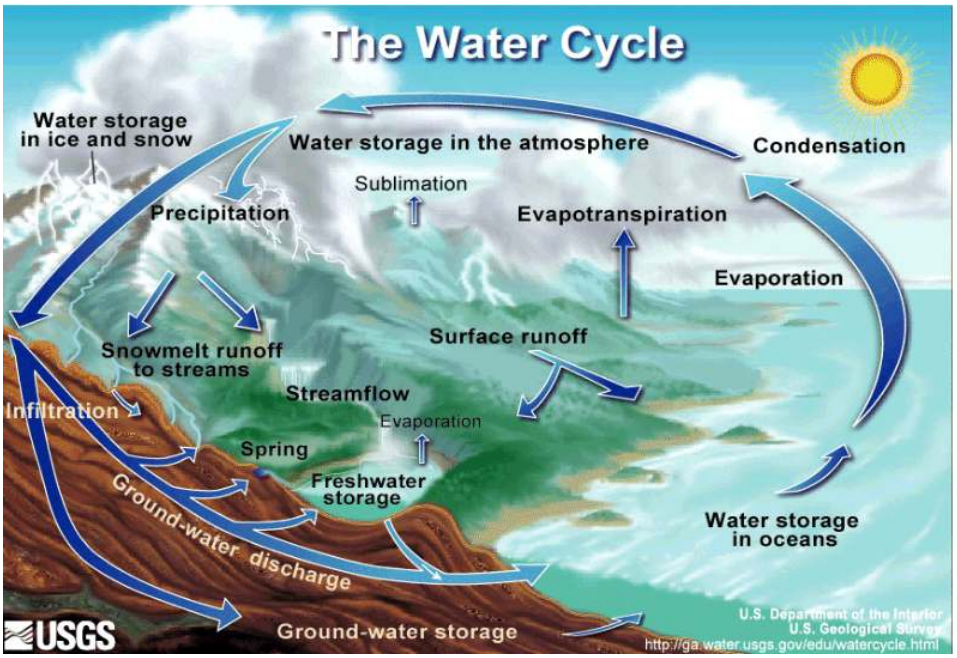


Figure 11.1.2. The Water Cycle. Arrows depict movement of water to different reservoirs located above, at, and below Earth's surface. Source: United States Geological Survey

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 11.1.3). 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.

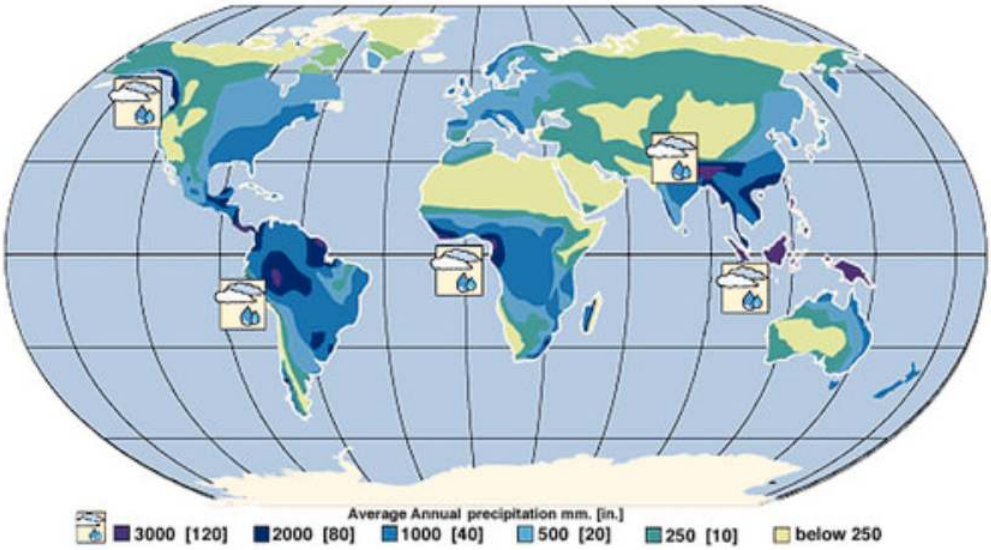


Figure 11.1.3. World Rainfall Map. The false-color map above shows the amount of rain that falls around the world. Areas of high rainfall include Central and South America, western Africa, and Southeast Asia. Since these areas receive so much rainfall, they are where most of the world's rainforests grow. 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



Figure 11.1.4. 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 11.1.4) and groundwater seepage (Figure 11.1.5). **River discharge** describes the volume of water moving through a river channel over time (Figure 11.1.6). 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 11.1.5. 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 11.1.6. 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 11.1.7. 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.

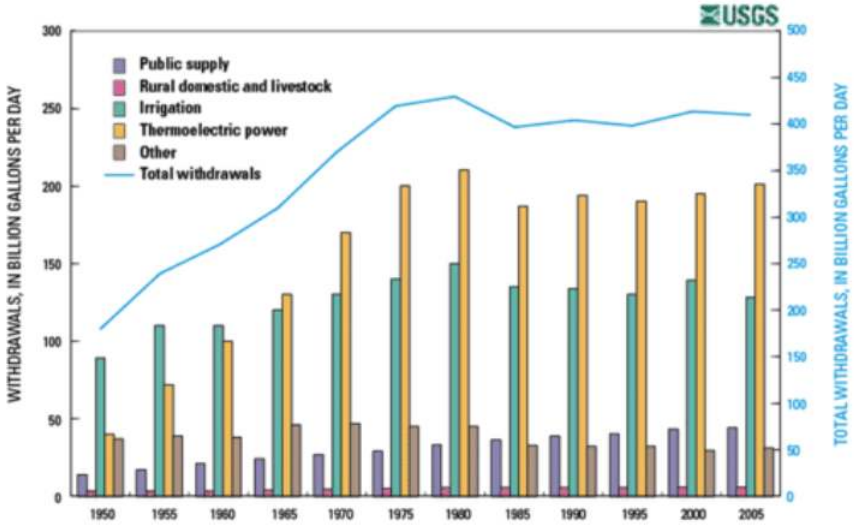


Figure 11.1.8. Trends in Total Water Withdrawals by Water-use Category, 1950-2005 Trends in total water withdrawals in the U.S. from 1950 to 2005 by water use category, including bars for thermoelectric power, irrigation, public water supply, and rural domestic and livestock. Thin blue line represents total water withdrawals using vertical scale on right. Source: United States Geological Survey

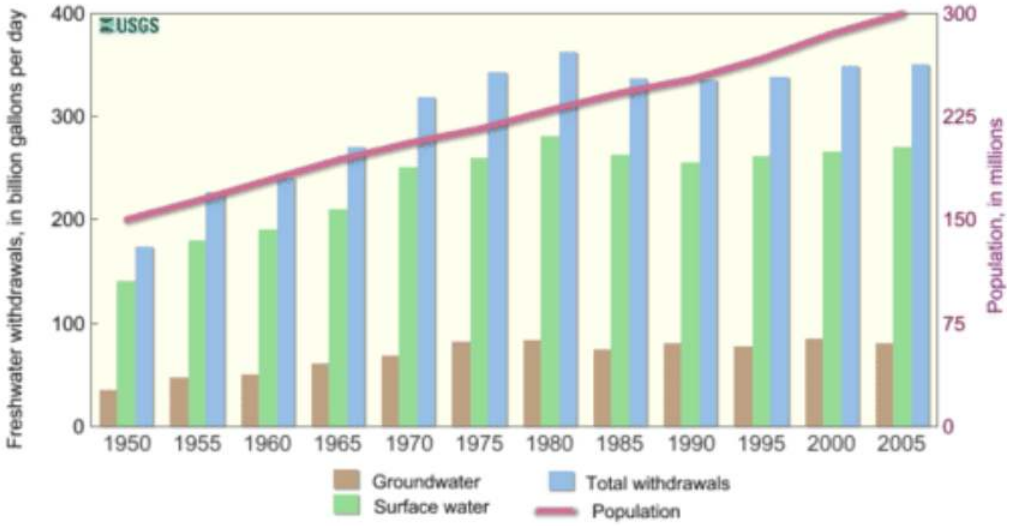


Figure 11.1.9. Trends in Source of Fresh Water Withdrawals in the U.S. from 1950 to 2005 Trends in source of fresh water withdrawals in the U.S. from 1950 to 2005, including bars for surface water, groundwater, and total water. Red line gives U.S. population using vertical scale on right. Source: United States Geological Survey

Global total water use is steadily increasing at a rate greater than world population growth (Figure 11.1.10). 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%).

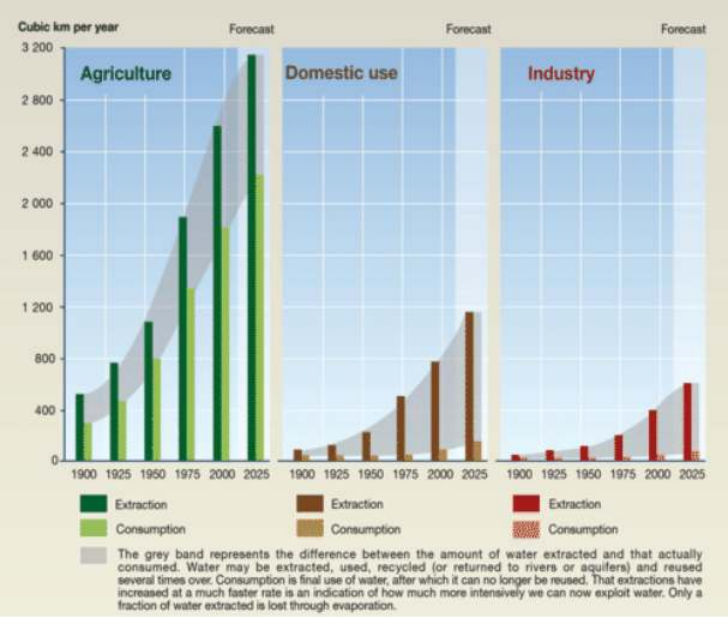


Figure 11.1.10. Trends in World Water Use from 1900 to 2000 and Projected to 2025 For each water major use category, including trends for agriculture, domestic use, and industry. Darker colored bar represents total water extracted for that use category and lighter colored bar represents water consumed (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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11.2: 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 artificial lakes (reservoirs) can also be depleted due to overuse. Some large rivers, such as the Colorado in the U.S. and Yellow in China, run dry in some years. The case history of the Aral Sea discussed later in this chapter involves depletion of a lake. Finally, glaciers are being depleted due to accelerated melting associated with global warming over the past century.

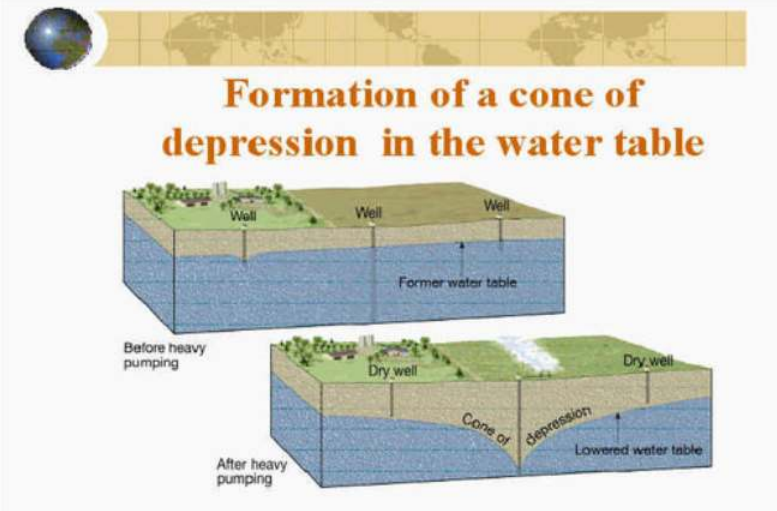


Figure 11.2.1. Formation of a Cone of Depression around a Pumping Water Well Source: Fayette County Groundwater Conservation District, TX

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. 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.

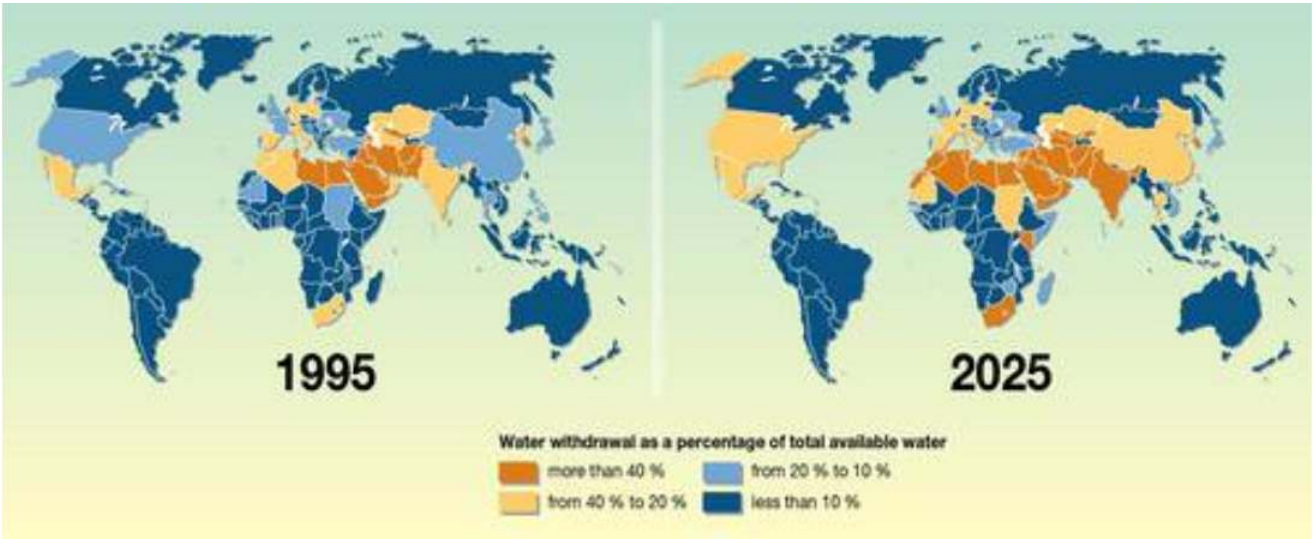


Figure 11.2.2. Countries Facing Water Stress in 1995 and Projected in 2025 Water stress is defined as having a high percentage of water withdrawal compared to total available water in the area. Source: Philippe Rekacewicz (Le Monde diplomatique), February 2006

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. 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 dams and aqueducts.

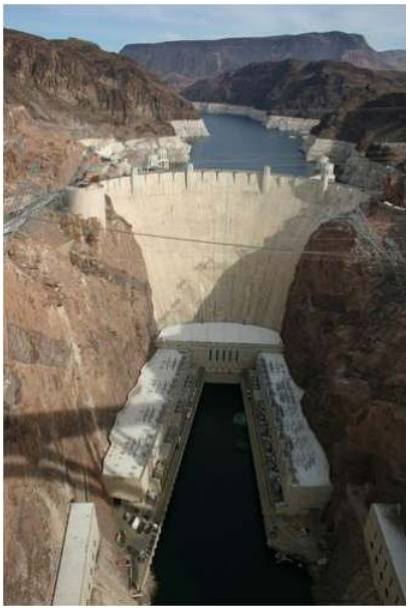


Figure 11.2.3. Hoover Dam, Nevada, U.S. Hoover Dam, Nevada, U.S.. Behind the dam is Lake Mead, the largest reservoir in U.S.. White band reflects the lowered water levels in the reservoir due to drought conditions from 2000 – 2010. Source: Cygnusloop99 at Wikimedia Commons

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.

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

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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11.3: 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 11.3.1, and 11.3.2 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.

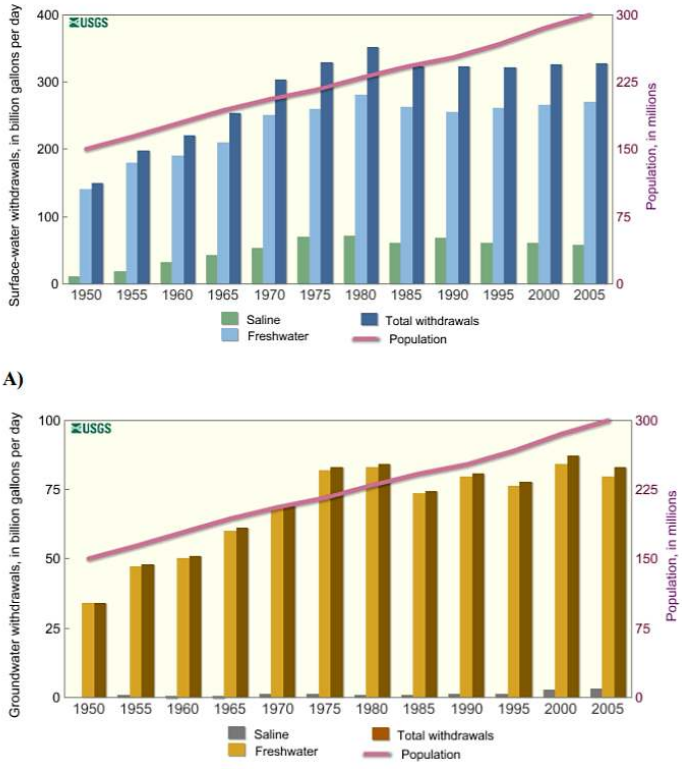


Figure 11.3.1: Trends in fresh and saline water withdrawals in response to population growth (A) surface water withdrawals (B) Groundwater withdrawal trends: water.usgs.gov/edu/wugw.html

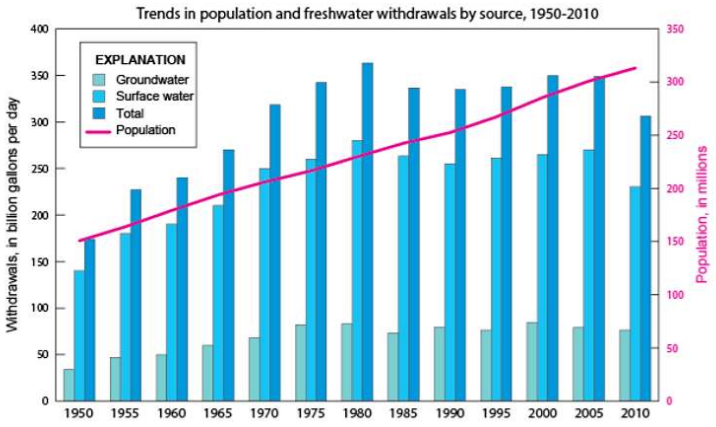


Figure 11.3.2: Both groundwater and surface water withdrawals had increased over time until 1980 when the withdrawals peaked and stabilized.

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 11.3.3 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 11.3.3: 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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11.4: 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 11.4.1). 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.

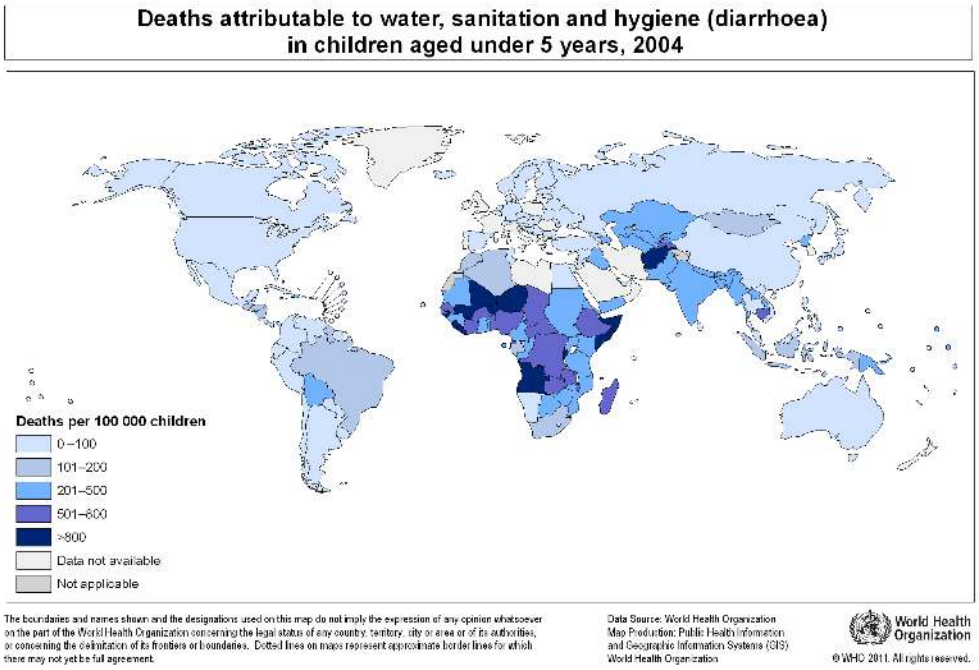


Figure 11.4.1. This work was created by the *World Health Organization*.

Any natural water contains dissolved chemicals, some of which are important human nutrients while others can 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.



Figure 11.4.2. Water Pollution. Obvious water pollution in the form of floating debris; invisible water pollutants sometimes can be much more harmful than visible ones. Source: Stephen Codrington at Wikimedia Commons

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 (Figure 11.4.2). Water pollutants can move through different water reservoirs, as the water carrying them progresses through stages of the water cycle (Figure 11.4.3). **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.

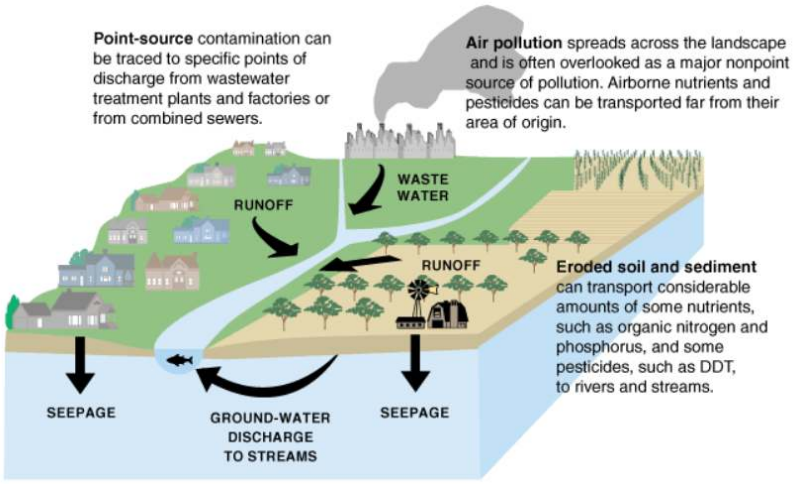


Figure 11.4.3. Sources of Water Contamination. Sources of some water pollutants and movement of pollutants into different water reservoirs of the water cycle. Source: U.S. Geological Survey

Pollutants enter water supplies from **point sources**, which are readily identifiable and relatively small locations, or **nonpoint sources**, which are large and more diffuse areas. Point sources of pollution include animal factory farms (Figure 11.4.4) 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 11.4.5).



Figure 11.4.4. Large animal farms are often referred to as concentrated feeding operations (CFOs). These farms are considered potential point sources of pollution because untreated animal waste may enter nearby waterbodies as untreated sewage. Credit: ehp.gov

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

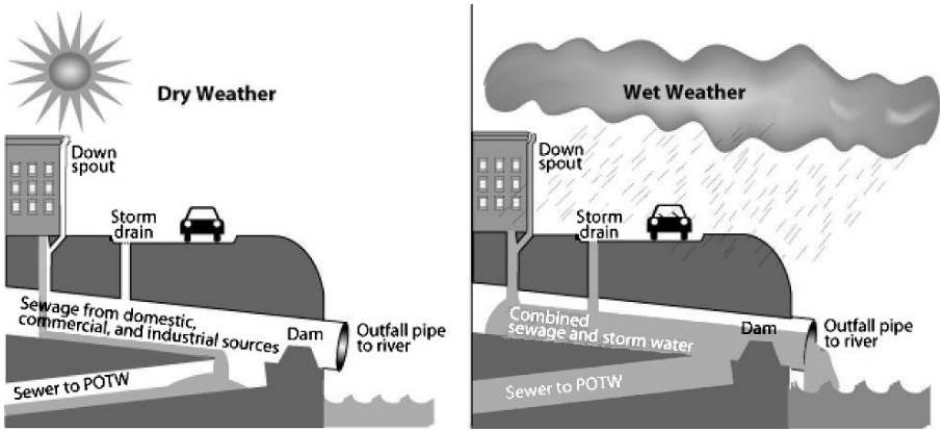


Figure 11.4.5. Combined Sewer System A combined sewer system is a possible major point source of water pollution during heavy rain due to overflow of untreated sewage. During dry weather (and small storms), all flows are handled by the publicly owned treatment works (POTW). During large storms, the relief structure allows some of the combined stormwater and sewage to be discharged untreated to an adjacent water body. Source: U.S. Environmental Protection Agency at Wikimedia Commons

Types of Water Pollutants

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

$$\text{organic matter} + O_2 \rightarrow CO_2 + H_2O \tag{11.4.1}$$

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** (in the presence of oxygen) bacterial decomposition of organic matter is

called **biochemical oxygen demand** (BOD). The major source of dead organic matter in many natural waters is sewage; 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 11.4.6) at an oil well 65 km offshore of Louisiana and flowed for 3 months in 2010, releasing an estimated 200 million gallons of oil. The worst oil spill ever occurred during the Persian Gulf war of 1991, when Iraq deliberately dumped approximately 200 million gallons of oil in offshore Kuwait and set more than 700 oil well fires that released enormous clouds of smoke and acid rain for over nine months.



Figure 11.4.6. Deepwater Horizon Explosion Boats fighting the fire from an explosion at the Deepwater Horizon drilling rig in Gulf of Mexico offshore Louisiana on April 20, 2010. Source: United States Coast Guard via Wikimedia Commons

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

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

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

Mercury (Hg) is used in a variety of electrical products, such as dry cell batteries, fluorescent light bulbs, and switches, as well as in the manufacture of paint, paper, vinyl chloride, and fungicides. Mercury acts on the central nervous system and can cause loss of sight, feeling, and hearing as well as nervousness, shakiness, and death. Like arsenic, mercury enters the water supply naturally from weathering of mercury-rich minerals and from human activities such as coal burning and metal processing. A famous mercury poisoning case in Minamata, Japan involved methylmercury-rich industrial discharge that caused high Hg levels in fish. People in

the local fishing villages ate fish up to three times per day for over 30 years, which resulted in over 2,000 deaths. During that time the responsible company and national government did little to mitigate, help alleviate, or even acknowledge the problem.

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

Groundwater pollution can occur from underground sources and all of the pollution sources that contaminate surface waters. Common sources of groundwater pollution are leaking underground storage tanks for fuel, septic tanks, agricultural activity, landfills, and fossil fuel extraction. Common groundwater pollutants include nitrate, pesticides, volatile organic compounds, and petroleum products. Another troublesome feature of groundwater pollution is that small amounts of certain pollutants, e.g., petroleum products and organic solvents, can contaminate large areas. In Denver, Colorado 80 liters of several organic solvents contaminated 4.5 trillion liters of groundwater and produced a 5 km long contaminant plume. A major threat to groundwater quality is from underground fuel storage tanks. Fuel tanks commonly are stored underground at gas stations to reduce explosion hazards. Before 1988 in the U.S. these storage tanks could be made of metal, which can corrode, leak, and quickly contaminate local groundwater. Now, leak detectors are required and the metal storage tanks are supposed to be protected from corrosion or replaced with fiberglass tanks. Currently there are around 600,000 underground fuel storage tanks in the U.S. and over 30% still do not comply with EPA regulations regarding either release prevention or leak detection.

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11.5: 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 11.5.1).

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.

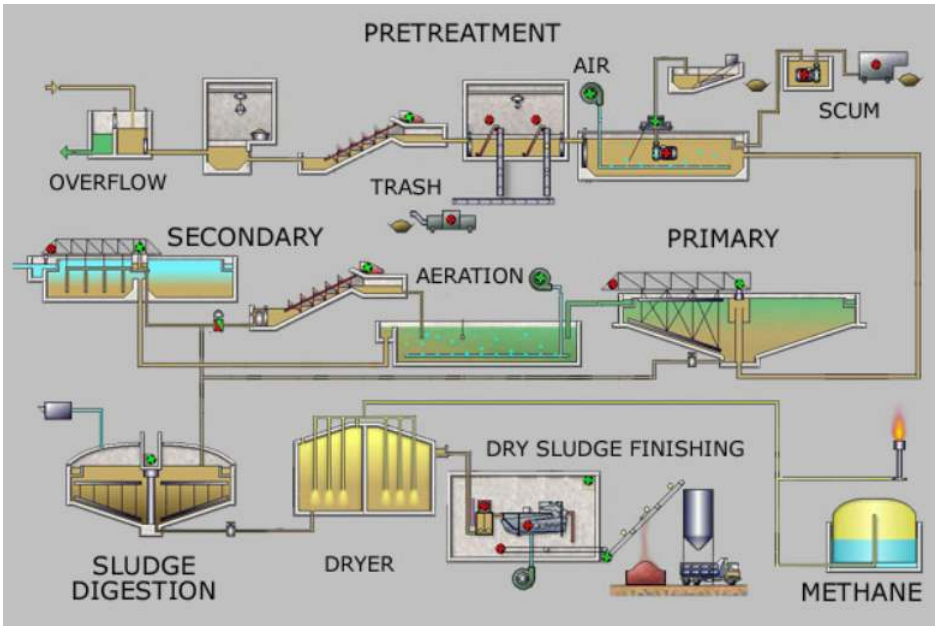


Figure 11.5.1. Steps at a Sewage Treatment Plant The numerous processing steps at a conventional sewage treatment plant include pretreatment (screening and removal of sand and gravel), primary treatment (settling or floatation to remove organic solids, fat, and grease), secondary treatment (aerobic bacterial 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 11.5.2) 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.

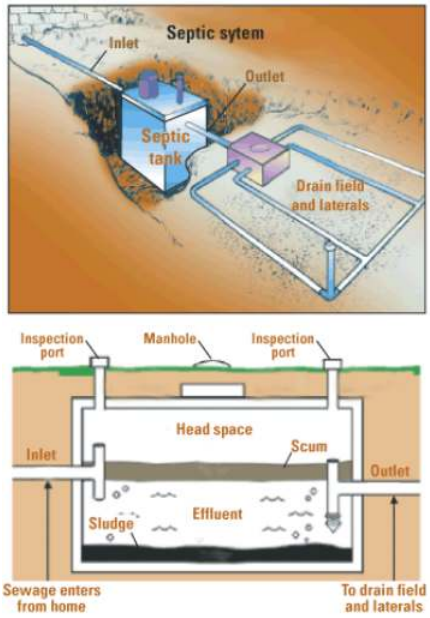


Figure 11.5.2. Septic System Septic tank system for sewage treatment. Source: United States Geological Survey

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 11.5.3. 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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11.6: 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.

Water in Crisis (case studies)

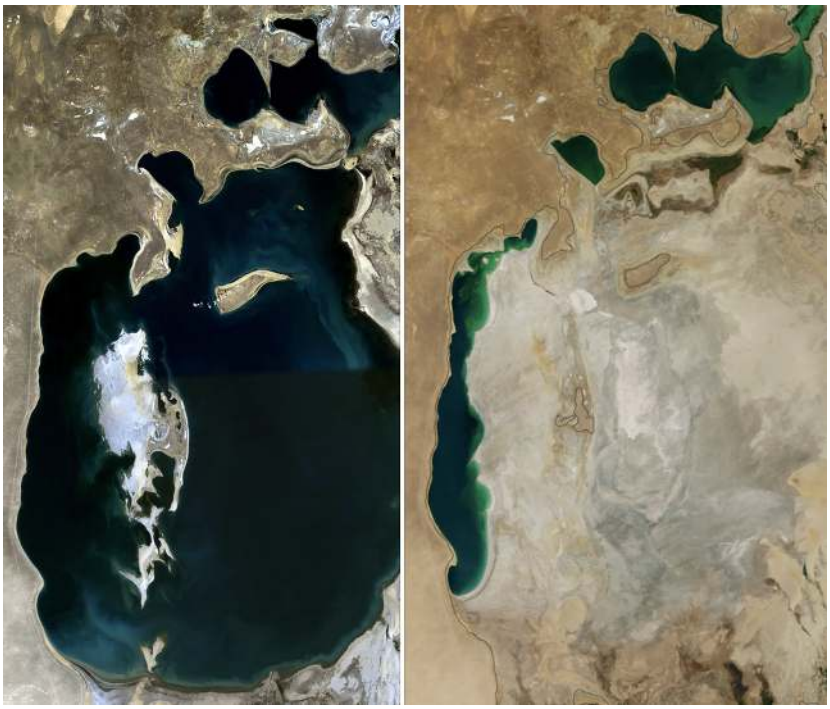
▪ Your instructor will assign you a specific case study for the course if needed.

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

The Aral Sea is a lake located east of the Caspian Sea between Uzbekistan and Kazakhstan in central Asia. This area is part of the Turkestan desert, which is the fourth largest desert in the world; it is produced from a rain shadow effect by Afghanistan's high mountains to the south. Due to the arid and seasonally hot climate there is extensive evaporation and limited surface waters in general. Summer temperatures can reach 60°C (140°F)! The water supply to the Aral Sea is mainly from two rivers, the Amu Darya and Syr Darya, which carry snow melt from mountainous areas.



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

In the early 1960s, the then-Soviet Union diverted the Amu Darya and Syr Darya Rivers for irrigation of one of the driest parts of Asia to produce rice, melons, cereals, and especially cotton. The Soviets wanted cotton or white gold to become a major export. They were successful, and, today Uzbekistan is one of the world's largest exporters of cotton. Unfortunately, this action essentially eliminated any river inflow to the Aral Sea and caused it to disappear almost completely.



Figure 11.7.2. Map of Aral Sea Area Map shows lake size in 1960 and political boundaries of 2011. Countries in yellow are at least partially in Aral Sea drainage basin. Source: Wikimedia Commons

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



Figure 11.7.3. This abandoned ship lies in a dried up lake bed that was the Aral Sea near Aral, Kazakhstan Source: Staecker at Wikimedia Commons

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

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11.8: Chapter Resources

Summary

Precipitation—a major control of fresh water availability—is unevenly distributed around the globe. More precipitation falls near the equator, and landmasses there are characterized by a tropical rainforest climate. Less precipitation tends to fall near 2030 north and south latitude, where the world's largest deserts are located. The water crisis refers to a global situation where people in many areas lack access to sufficient water or clean water or both. The current and future water crisis requires multiple approaches to extending our fresh water supply and moving towards sustainability. Some of the longstanding traditional approaches include dams and aqueducts. Water pollution is the contamination of water by an excess amount of a substance that can cause harm to human beings and the ecosystem. The level of water pollution depends on the abundance of the pollutant, the ecological impact of the pollutant, and the use of the water. The most deadly form of water pollution, pathogenic microorganisms that cause waterborne diseases, kills almost 2 million people in underdeveloped countries every year. Resolution of the global water pollution crisis requires multiple approaches to improve the quality of fresh water. The best strategy for addressing this problem is proper sewage treatment. Untreated sewage is not only a major cause of pathogenic diseases, but also a major source of other pollutants, including oxygen-demanding waste, plant nutrients, and toxic heavy metals.

Review Questions

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

See Appendix for answers

Attributions

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

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CHAPTER OVERVIEW

12: Environmental Geology and Resources

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12.1: Introduction to Geology

What is Geology?

In its broadest sense, geology is the study of Earth—its interior and its exterior surface, the minerals, rocks and other materials that are around us, the processes that have resulted in the formation of those materials, the water that flows over the surface and through the ground, the changes that have taken place over the vastness of geological time, and the changes that we can anticipate will take place in the near future. Geology is a science, meaning that we use deductive reasoning and scientific methods to understand geological problems. It is, arguably, the most integrated of all of the sciences because it involves the understanding and application of all of the other sciences: physics, chemistry, biology, mathematics, astronomy, and others. But unlike most of the other sciences, geology has an extra dimension, that of time—deep time—billions of years of it. Geologists study the evidence that they see around them, but in most cases, they are observing the results of processes that happened thousands, millions, and even billions of years in the past. Those were processes that took place at incredibly slow rates—millimeters per year to centimeters per year—but because of the amount of time available, they produced massive results.

Geology is displayed on a grand scale in mountainous regions, perhaps nowhere better than the Rocky Mountains in Canada (Figure 12.1.1). The peak on the right is Rearguard Mountain, which is a few kilometers northeast of Mount Robson, the tallest peak in the Canadian Rockies (3,954 meters). The large glacier in the middle of the photo is the Robson Glacier. The river flowing from Robson Glacier drains into Berg Lake in the bottom right. There are many geological features portrayed here. The sedimentary rock that these mountains are made of formed in ocean water over 500 million years ago. A few hundred million years later, these beds were pushed east for tens to hundreds of kilometers by tectonic plate convergence and also pushed up to thousands of meters above sea level. Over the past two million years this area—like most of the rest of Canada—has been repeatedly glaciated, and the erosional effects of those glaciations are obvious. The Robson Glacier is now only a small remnant of its size during the Little Ice Age of the 15th to 18th centuries, and even a lot smaller that it was just over a century ago in 1908. The distinctive line on the slope on the left side of both photos shows the elevation of the edge of the glacier a few hundred years ago. Like almost all other glaciers in the world, it receded after the 18th century because of natural climate change, is now receding even more rapidly because of human-caused climate change.



Figure 12.1.1: Rearguard Mountain and Robson Glacier in Mount Robson Provincial Park, BC. Left: Robson Glacier in 2012. Right: Robson Glacier circa 1908.
(left): © Steven Earle. CC BY. (right): A.P. Coleman. Public domain. Source: Arthur P. Coleman Collection at Victoria University Library.

How Earth Formed

The **Big Bang** (12-15 billion years ago) produced the atoms of hydrogen and helium. Elements as heavy as lithium followed the Big Bang within minutes. Eventually, under the pervasive influence of gravity, the hydrogen and helium were aggregated into immense masses that became increasingly compressed under enormously high pressure and temperature. When the pressure and temperature were sufficiently intense, nuclear fusion reactions began to occur within the masses, at which point they had become young stars. Stars such as red giants fused hydrogen and helium nuclei to form elements from carbon (the foundation of life) to

calcium (now our bones and teeth). Supernova explosions formed and ejected heavier elements such as iron (for red blood cells). Hydrogen and helium are still, however, the most abundant elements, comprising more than 99.9% of the mass of the universe.

The Sun is an ordinary star, one of billions of billions that exist in the universe. The Sun, its eight orbiting planets, plus miscellaneous comets, meteors, asteroids, and other materials (such as space dust) are collectively known as the solar system. This particular region of the universe is organized and held together by a balance of the attractive force of gravitation and counteracting influences associated with rotation and orbiting (these same forces, along with continuing expansion from the initial big bang, also organize the universe). The age of the solar system (and of Earth) is at least 4.6 billion years. The solar system began as a rotating cloud of stardust. About 4.6 billion years ago, a nearby star exploded and sent a shock wave through the dust cloud, increasing its rate of spin. As a result, most of the mass became concentrated in the middle, forming the sun. Smaller concentrations of mass rotating around the center formed the planets, including Earth.

You can watch a video showing how Earth formed at this link:http://www.youtube.com/watch?v=-x8-KMR0nx8.

Earth is the third-closest planet to the Sun. Earth is a dense planet, as are other so-called terrestrial planets located relatively close to the Sun: Mercury, Venus, and Mars. The mass of these planets consists almost entirely of heavier elements such as iron, nickel, magnesium, aluminum, and silicon. These inner planets were formed by a selective condensing of heavier elements out of the primordial planetary nebula (the disk of gases and other matter that slowly rotated around the Sun during the early stages of formation of its solar system). This happened because the inner planets were subjected to relatively intense heating by solar radiation, which caused lighter gases such as hydrogen and helium to disperse further away, to the extent that they ended up mostly in the outer, cooler planets. Meanwhile the terrestrial planets retained heavier elements. Consequently, the more distant planets in the solar system, such as Jupiter and Saturn, are relatively large, gaseous, and diffuse in character. Most of their volume is composed of an extensive atmosphere of hydrogen and helium, although these planets may contain heavier elements in their core.

At first, Earth was molten and lacked an atmosphere and oceans. The main source of heat at that time was probably the decay of naturally-occurring radioactive elements. Gradually, the planet cooled and formed a solid crust. As the planet continued to cool, volcanoes released gases, which eventually formed an **atmosphere**. The early atmosphere contained ammonia, methane,water vapor, and carbon dioxide but only a trace of oxygen. As the atmosphere became denser, clouds formed and rain fell. Water from rain, and perhaps from comets and asteroidsthat struck Earth as well, eventually formed the oceans. The ancient atmosphere and oceans represented by the picture in Figure 12.1.2 would be toxic to today's life, but they set the stage for life to begin.



Figure 12.1.2**:** Ancient Earth. This is how ancient Earth may have looked after its atmosphere and oceans formed.

Geological Time

In 1788, after many years of geological study, James Hutton, one of the great pioneers of geology, wrote the following about the age of Earth: *The result, therefore, of our present enquiry is, that we find no vestige of a beginning — no prospect of an end.*[1] Of course he wasn't exactly correct, there was a beginning and there will be an end to Earth, but what he was trying to express is that geological time is so vast that we humans, who typically live for less than a century, have no means of appreciating how much geological time there is. Hutton didn't even try to assign an age to Earth, but we now know that it is approximately 4,570 million years old. Using the scientific notation for geological time, that is 4,570 **Ma** (for *mega annum* or "millions of years") or 4.57 **Ga**

(for *gigaannum* or billions of years). More recent dates can be expressed in **ka** (*kiloannum*); for example, the last cycle of glaciation ended at approximately 11.7 ka or 11,700 years ago.

In order to describe the time relationships between rock formations and fossils, scientists developed a relative **geologic time scale** in which the earth's history is divided and subdivided into time divisions. The three eons (**Phanerozoic**, **Proterozoic**, and **Archean**) represent the largest time divisions (measured in billions of years). They in turn are subdivided into **Eras**, **Periods** and **Epochs**. Major discontinuities in the geologic record and in the corresponding biological (fossil) record are chosen as boundary lines between the different time segments. For example, the Cretaceous-Tertiary boundary (65 million years ago) marks a sudden mass extinction of species, including the dinosaurs. Through the use of modern quantitative techniques, some rocks and organic matter can be accurately dated using the decay of naturally-occurring radioactive isotopes. Therefore, absolute ages can be assigned to some parts of the geologic time scale.

A version of the geological time scale is included as Figure 12.1.3. Unlike time scales you'll see in other places, or even later in this book, this time scale is linear throughout its length, meaning that 50 Ma during the **Cenozoic** is the same thickness as 50 Ma during the **Hadean**—in each case about the height of the "M" in Ma. The Pleistocene glacial epoch began at about 2.6 Ma, which is equivalent to half the thickness of the thin grey line at the top of the yellow bar marked "Cenozoic." Most other time scales have earlier parts of Earth's history compressed so that more detail can be shown for the more recent parts. That makes it difficult to appreciate the extent of geological time.

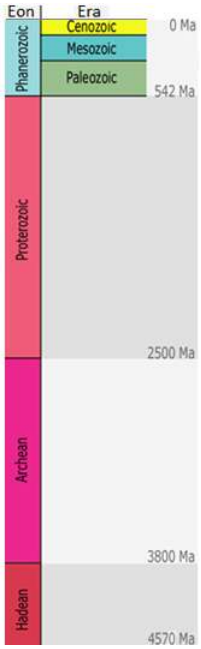


Figure 12.1.3 The geological time scale. The Hadean eon (3800 Ma to 4570 Ma), Archean eon (2500 Ma to 3800 Ma), and Proterozoic eon (542 Ma to 2500 Ma) make up 88% of geological time. The Phanerozoic eon makes up the last 12% of geological time. The Phanerozoic eon (0 Ma to 542 Ma) contains the Paleozoic, Mesozoic, and Cenozoic eras. © Steven Earle. CC BY.

To create some context, the **Phanerozoic** Eon (the last 542 million years) is named for the time during which visible (*phaneros*) life (*zoi*) is present in the geological record. In fact, large organisms—those that leave fossils visible to the naked eye—have existed for a little longer than that, first appearing around 600 Ma, or a span of just over 13% of geological time. Animals have been on land for 360 million years, or 8% of geological time. Mammals have dominated since the demise of the dinosaurs around 65 Ma, or 1.5% of geological time, and the genus *Homo* has existed since approximately 2.8 Ma, or 0.06% (1/1,600th) of geological time.

Geologists (and geology students) need to understand geological time. That doesn't mean memorizing the geological time scale; instead, it means getting your mind around the concept that although most geological processes are extremely slow, very large and important things can happen if such processes continue for enough time.

For example, the Atlantic Ocean between Nova Scotia and northwestern Africa has been getting wider at a rate of about 2.5 centimeters (cm) per year. Imagine yourself taking a journey at that rate—it would be impossibly and ridiculously slow. And yet,

since it started to form at around 200 Ma (just 4% of geological time), the Atlantic Ocean has grown to a width of over 5,000 kilometers (km)!

A useful mechanism for understanding geological time is to scale it all down into one year. The origin of the solar system and Earth at 4.57 Ga would be represented by January 1, and the present year would be represented by the last tiny fraction of a second on New Year's Eve. At this scale, each day of the year represents 12.5 million years; each hour represents about 500,000 years; each minute represents 8,694 years; and each second represents 145 years. Some significant events in Earth's history, as expressed on this time scale, are summarized on Table 12.1.1.

Table 12.1.1 A summary of some important geological dates expressed as if all of geological time was condensed into one year.

[Skip Table]

Event	Approximate Date	Calendar Equivalent
Formation of oceans and continents	4.5 to 4.4 Ga	January
Evolution of the first primitive life forms	3.8 Ga	early March
Formation of British Columbia's oldest rocks	2.0 Ga	July
Evolution of the first multi-celled animals	0.6 Ga or 600 Ma	November 15
Animals first crawled onto land	360 Ma	December 1
Vancouver Island reached North America and the Rocky Mountains were formed	90 Ma	December 25
Extinction of the non-avian dinosaurs	65 Ma	December 26
Beginning of the Pleistocene ice age	2 Ma or 2000 ka	8 p.m., December 31
Retreat of the most recent glacial ice from southern Canada	14 ka	11:58 p.m., December 31
Arrival of the first people in British Columbia	10 ka	11:59 p.m., December 31
Arrival of the first Europeans on the west coast of what is now Canada	250 years ago	2 seconds before midnight, December 31

References

1. Hutton, J, 1788. Theory of the Earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the Globe. Transactions of the Royal Society of Edinburgh. ↵

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12.2: Earthquakes

An earthquake is the shaking caused by the **rupture** (breaking) and subsequent displacement of rocks (one body of rock moving with respect to another) beneath Earth's surface. A body of rock that is under stress becomes deformed. When the rock can no longer withstand the deformation, it breaks and the two sides slide past each other. The region where the rupture occurs is called the **focus**. This is often deep below the surface of the crust. The point on the surface directly above the focus is called the **epicenter**. Destructive waves propagate outward from the region of the quake, traveling throughout the earth. The magnitude of an earthquake is a measure of the total amount of energy released. The first step in determining the magnitude is to measure the propagated waves using a device called a **seismograph**. Based on this information, the earthquake is given a number classification on a modified **Richter scale**. The scale is logarithmic, so a difference of one unit means a difference of ten-fold in wave intensity, which corresponds to an energy difference of 32-fold. The intensity of an earthquake is an indicator of the effect of an earthquake at a particular locale. The effect depends not only on the magnitude of the earthquake, but also the types of subsurface materials and the structure and design of surface structures.

Earthquakes generally occur along breaks in the rock mass known as **faults**, and most occur in regions near plate boundaries, although not all earthquakes happen on pre-existing faults. Some 80 percent of all earthquakes occur near convergent plate boundaries, triggered by the interaction of the plates. Earthquakes are also often associated with volcanic activity due to the movement of sub-surface magma.

An intense earthquake can cause great damage to buildings, and the collapsing structures, fires, and other destruction can take a great toll on people. In 1556 an earthquake struck Shanxi Province in China and caused about 830,000 deaths, making it the most deadly earthquake in recorded history. The most famous catastrophic earthquake in North America was the San Francisco event in 1906, caused by slippage along the San Andreas Fault, which killed 503 people and resulted in tremendous physical damage. However, other earthquakes during the twentieth century resulted in much greater losses of human lives, including one in 1976 that killed 242,000 people in Tangshan, China; another in 1927 that killed 200,000 in Nan-Shan, China; and one in Tokyo–Yokohama, Japan, that killed 200,000 in 1926. Notable recent earthquakes include one in Kobe, Japan (1995) that killed 5,500 people, another in Kashmir (2005) that killed 79,000 people, one in Sichuan, China (2008) that killed 70,000 people, and one in the Tohuku region of Japan (2011) that generated a tsunami (seismic sea wave) that killed 16,000 people. The events in San Francisco (1906) and Tokyo (1926) affected large cities. The powerful tremors caused great damage, partly because of weak architectural designs that were unable to withstand the strong forces. In both cases, however, about 90% of the actual destruction resulted from fires. Earthquakes can also cause soil to lose some of its mechanical stability, resulting in destructive landslides and subsidence (sinking) of land and buildings.

When an earthquake occurs under the ocean, it can trigger a destructive tidal wave known as a **tsunami**. A tsunami may be almost indiscernible in deep water of the open ocean, but it can become gigantic when the wave reaches shallow water and piles up to heights that can swamp coastal villages and towns. In 1946, a large earthquake centered on Umiak Island in the Aleutian Islands (Alaska) caused a tsunami to strike Hawaii, 4,500 km away, with an 18 m crest. The greatest tsunami of recent times was triggered by an undersea, so-called "megathrust" earthquake on December 26, 2004. Its epicenter was located about 40 km off the coast of Aceh in northern Sumatra, an Indonesian island, and it registered a massive 9.2 on the Richter scale (making it the largest earthquake in 40 years) (Figure 12.2.1). The tremor generated an immense tsunami (actually, a close series of individual waves) that gathered to a height up to 30 m when it impacted shallow-sloping coasts of countries fringing the Indian Ocean. The colossal tsunami waves were moving at speeds of about 60 kmhr when they impacted the shore. They caused widespread devastation and more than 225,000 deaths by drowning and injuries caused by floating debris and collapsing buildings. The hardest-hit places were Sumatra (which suffered at least 168,000 dead and missing), Sri Lanka (35,000), the eastern coast and islands of India (18,000), and Thailand (8,000). At least 7,000 of the deaths were tourists from developed countries who were visiting coastal resorts during their holiday break. In addition to the mortality, tens of millions of people were displaced from their homes and livelihoods by the flooding. In many of the worst-hit places, the damage was made much more severe because of increased coastal vulnerability caused by the removal of previously abundant mangrove forest, mostly to develop tourist resorts and brackish ponds for shrimp aquaculture. Where mangroves remained intact, the coastal forest provided a sea-wall that helped to absorb much of the force of the tsunami, providing a measure of protection to areas further inland.



Figure 12.2.1: A devastated village on the coast of Aceh, Sumatra, after the killer tsunami of December 26, 2004. Source: image by P.A. McDaniel, United States Navy, ID 050102-N-9593M-040; https://commons.wikimedia.org/wiki/File%3AUS_Navy_050102-N-9593M-040_A_village_near_the_coast_of_Sumatra_lays_in_ruin_after_the_Tsunami_that_struck_South_East_Asia.jpg

Earthquake Processes

The engineering principle of **elastic deformation**, which can be used to understand earthquakes, is illustrated in Figure 12.2.2. The stress applied to a rock—typically because of ongoing plate movement—results in strain or deformation of the rock (Figure 12.2.2 b). Because most rock is strong (unlike loose sand, for example), it can withstand a significant amount of deformation without breaking. But every rock has a deformation limit and will rupture (break) once that limit is reached. At that point, in the case of rocks within the crust, the rock breaks and there is displacement along the **rupture surface** (Figure 12.2.2c). The magnitude of the earthquake depends on the extent of the area that breaks (the area of the rupture surface) and the average amount of displacement (sliding).

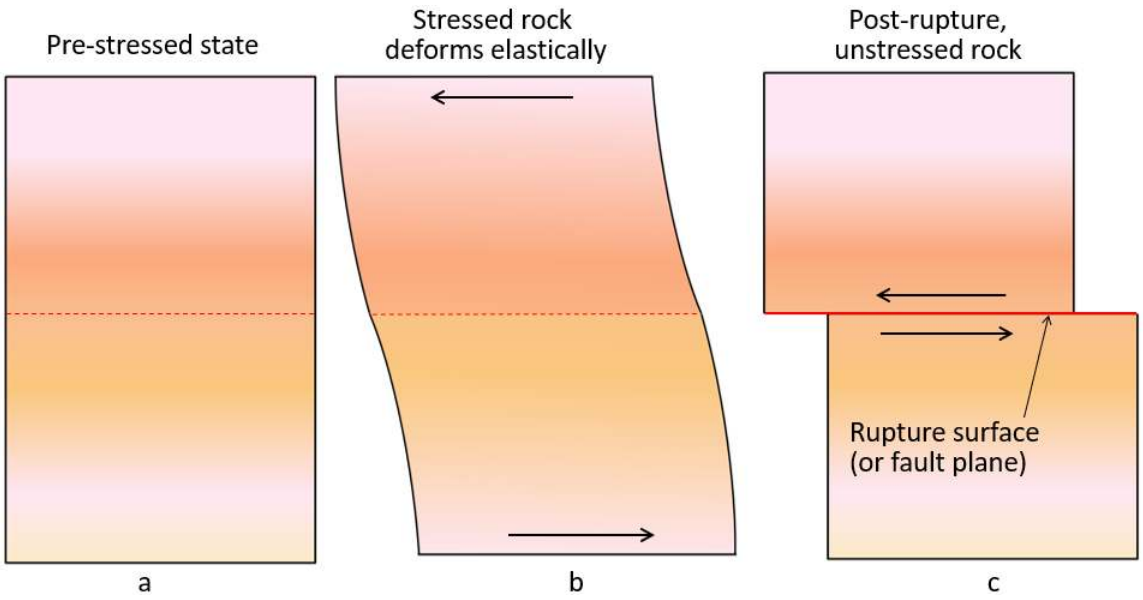


Figure 12.2.2 Depiction of the concept of elastic deformation and rupture. The plate boundary is shown as a dashed red line. In b the two plates are moving as shown by the arrows, but they are locked against each along the plate boundary so they are both deforming and the rocks are stressed. In c there has been a rupture along the boundary and the stress is released. © Steven Earle. CC BY

The concept of a rupture surface, which is critical to understanding earthquakes, is illustrated in Figure 12.2.3. An earthquake does not happen at a point, it happens over an area within a plane, although not necessarily a *flat* plane. Within the area of the rupture surface, the amount of displacement is variable (Figure 12.2.3), and, by definition, it decreases to zero at the edges of the rupture surface because the rock beyond that point isn't displaced at all. The extent of a rupture surface and the amount of displacement will depend on a number of factors, including the type and strength of the rock, and the degree to which it was stressed beforehand.

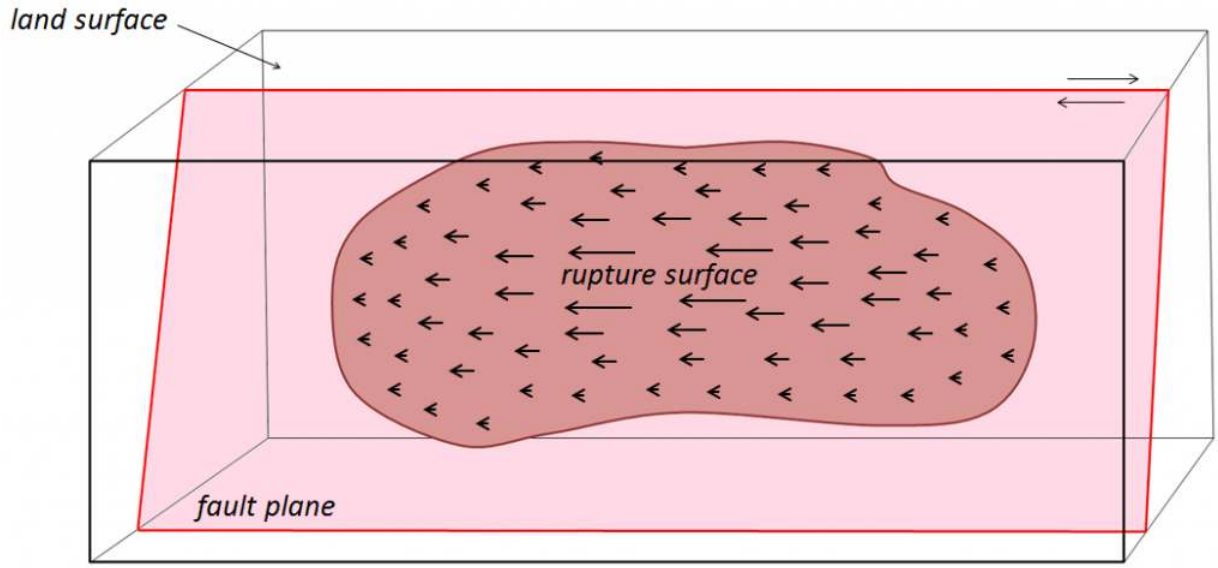


Figure 12.2.3 A rupture surface (dark pink), on a steeply dipping fault plane (light pink). The diagram represents a part of the crust that may be up to tens or hundreds of kilometers long. The rupture surface is the part of the fault plane along which displacement occurred. In this example, the near side of the fault is moving to the left, and the lengths of the arrows within the rupture surface represent relative amounts of displacement. © Steven Earle. CC BY

Earthquake rupture doesn't happen all at once; it starts at a single point and spreads rapidly from there. Depending on the extent of the rupture surface, the propagation of failures out from the point of initiation is typically completed within seconds to several tens of seconds (Figure 12.2.4). The initiation point isn't necessarily in the centre of the rupture surface; it may be close to one end, near the top, or near the bottom.

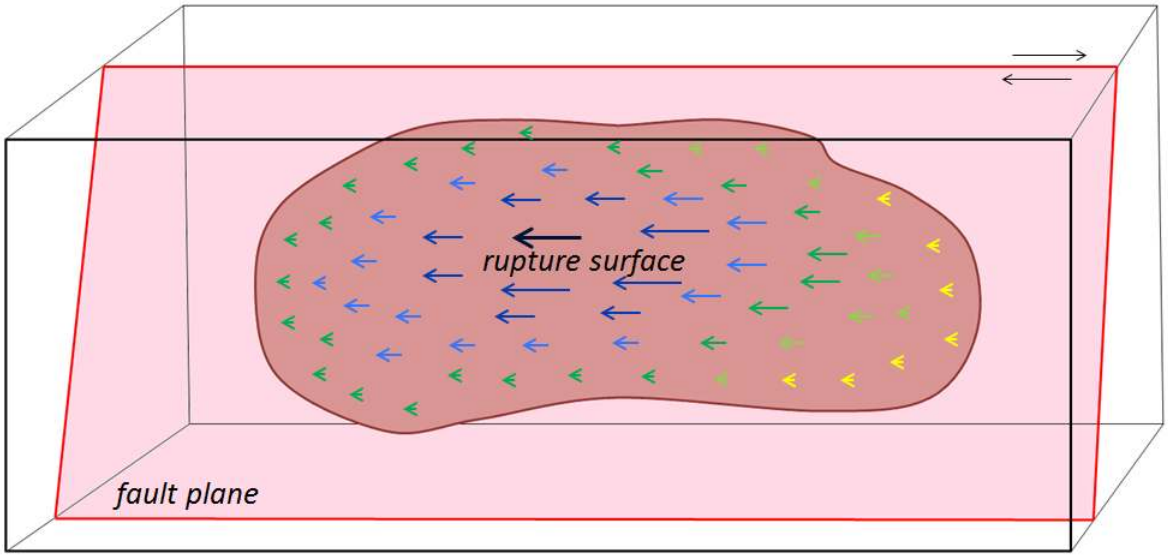


Figure 12.2.4 Propagation of failure on a rupture surface. In this case, the failure starts at the dark blue heavy arrow in the centre and propagates outward, reaching the left side first (green arrows) and the right side last (yellow arrows). © Steven Earle. CC BY

Figure 12.2.5 shows the distribution of immediate **aftershocks** associated with the 1989 Loma Prieta earthquake. Panel (b) is a section along the San Andreas Fault; this view is equivalent to what is shown in Figures 12.2.3 and 12.2.4. The area of red dots is the rupture surface; each red dot is a specific aftershock that was recorded on a seismometer. The hexagon labelled "main earthquake" represents the first or main shock. When that happened, the rock at that location broke and was displaced. That released the stress on that particular part of the fault, but it resulted in an increase of the stress on other nearby parts of the fault, and contributed to a cascade of smaller ruptures (aftershocks), in this case, over an area about 60 kilometers long and 15 kilometers wide.

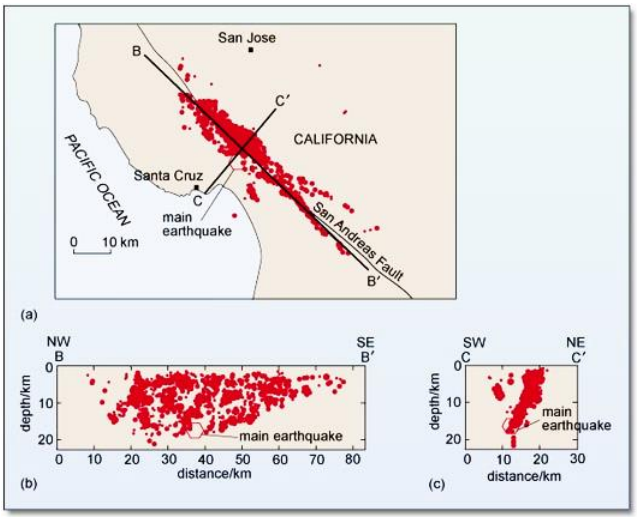


Figure 12.2.5 Distribution of the aftershocks of the 1989 M 6.9 Loma Prieta earthquake (a: plan view, b: section along the fault, c: section across the fault.) © Open University. CC BY-SA.

So, what exactly is an aftershock then? An aftershock is an earthquake just like any other, but it is one that can be shown to have been triggered by **stress transfer** from a preceding earthquake. Within a few tens of seconds of the main Loma Prieta earthquake, there were hundreds of smaller aftershocks; their distribution defines the area of the rupture surface.

Aftershocks can be of any magnitude. Most are smaller than the earthquake that triggered them, but they can be bigger. The aftershocks shown in Figure 12.2.4 all happened within seconds or minutes of the main shock, but aftershocks can be delayed for hours, days, weeks, or even years. As already noted, aftershocks are related to stress transfer. For example, the main shock of the Loma Prieta earthquake triggered aftershocks in the immediate area, which triggered more in the surrounding area, eventually extending for 30 kilometers along the fault in each direction and for 15 kilometers toward the surface. But the earthquake as a whole also changed the stress on adjacent parts of the San Andreas Fault. This effect, which has been modelled for numerous

earthquakes and active faults around the world, is depicted in Figure 12.2.6. Stress was reduced in the area of the rupture (blue), but was increased at either end of the rupture surface (red and yellow).

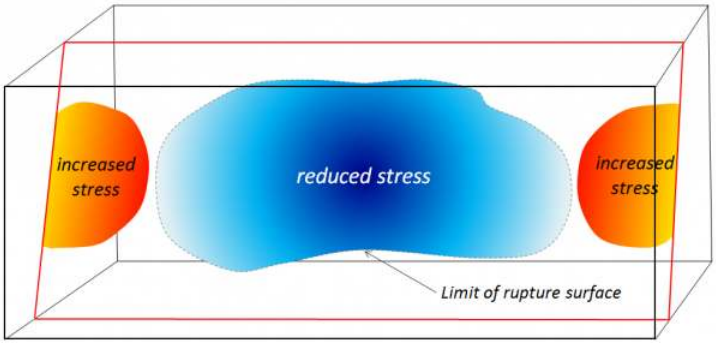


Figure 12.2.6 Depiction of stress changes related to an earthquake. Stress decreases in the area of the rupture surface, but increases on adjacent parts of the fault. © Steven Earle. CC BY. Based on data from 2010 Laguna Salada earthquake by Stein and Toda.

Stress transfer isn't necessarily restricted to the fault along which an earthquake happened. It will affect the rocks in general around the site of the earthquake and may lead to increased stress on other faults in the region. The effects of stress transfer don't necessarily show up right away. Segments of faults are typically in some state of stress, and the transfer of stress from another area is only rarely enough to push a fault segment beyond its limits to the point of rupture. The stress that is added by stress transfer accumulates along with the ongoing buildup of stress from plate motion and eventually leads to another earthquake.

Episodic Tremor and Slip

Episodic tremor and slip (ETS) is periodic slow sliding along part of a subduction boundary. It does not produce recognizable earthquakes, but does produce seismic tremor (rapid seismic vibrations on a seismometer). It was first discovered on the Vancouver Island part of the Cascadia subduction zone by Geological Survey of Canada geologists Herb Dragert and Garry Rogers.[1]

The boundary between the subducting Juan de Fuca Plate and the North America Plate can be divided into three segments (Figure 12.2.7). The cold upper part of the Juan de Fuca Plate boundary is locked. The plates are stuck and don't move, except with very large earthquakes that happen *approximately* every 500 years (the last one was approximately M9 on January 26, 1700). The warm lower part of the boundary is sliding continuously because the warm rock is weaker. The central part of the boundary isn't cold enough to be stuck, but isn't warm enough to slide continuously. Instead it slips episodically, approximately every 14 months for about 2 weeks, moving a few centimeters each time.

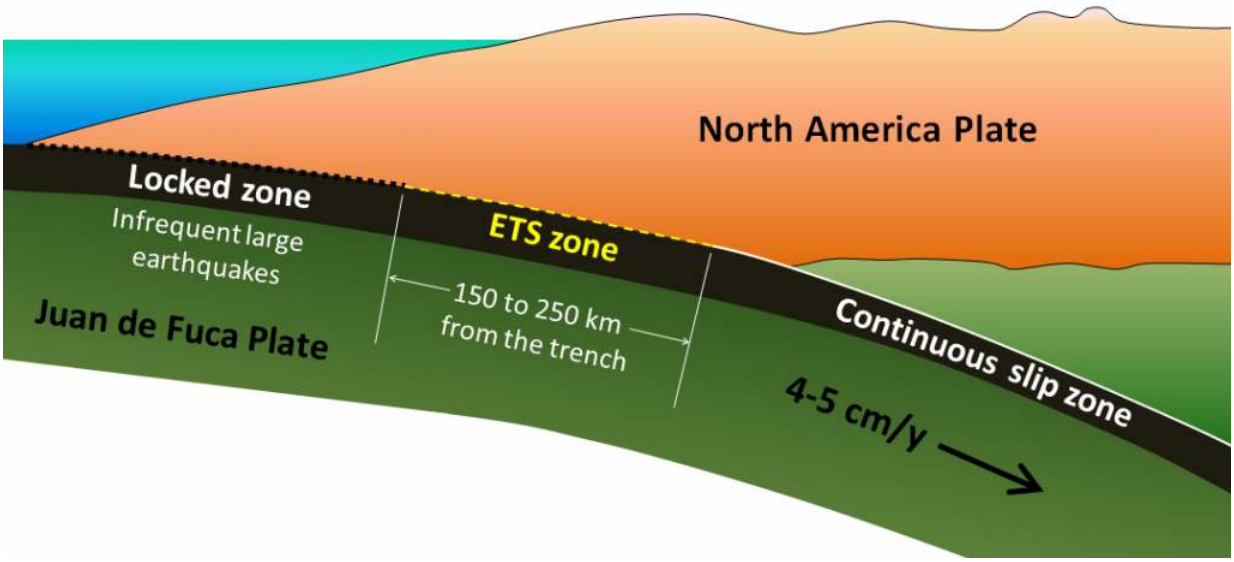


Figure 12.2.7 The boundary between the subducting Juan de Fuca Plate and the North America Plate is locked in the upper part, slides continuously in the lower part and slides episodically in the middle part. © Steven Earle. CC BY

You might be inclined to think that it's a good thing that there is periodic slip on this part of the plate because it releases some of the tension and reduces the risk of a large earthquake. In fact, the opposite is likely the case. The movement along the ETS part of the plate boundary acts like a medium-sized earthquake and leads to stress transfer to the adjacent locked part of the plate. Approximately every 14 months, during the two-week ETS period, there is a transfer of stress to the shallow locked part of the Cascadia subduction zone, and therefore an increased chance of a large earthquake.

Since 2003, ETS processes have also been observed on subduction zones in Mexico, New Zealand and Japan.

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1. Rogers, G. and Dragert, H., 2003, Episodic tremor and slip on the Cascadia subduction zone: the chatter of silent slip, Science, V. 300, p. 1942-1943. ↵

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12.3: Volcanoes

A volcano is any location where magma comes to the surface, or has done so within the past several million years (Figure 12.3.1). This can include eruptions on the ocean floor (or even under the water of lake), where they are called **subaqueous eruptions**, or on land, where they are called **subaerial eruptions**. Volcanoes commonly occur near plate boundaries where the motion of the plates has created cracks in the lithosphere through which the magma can flow. About eighty percent of volcanoes occur at convergent plate boundaries where subducted material melts and rises through cracks in the crust. Not all volcanic eruptions produce the volcanic mountains with which we are familiar; in fact most of Earth's volcanism takes place along the spreading ridges on the sea floor and does not produce volcanic mountains at all — not even sea-floor mountains.



***Figure** 12.3.1**:** Mt. Garibaldi (background left, looking from the north) with Garibaldi Lake in the foreground. Mt. Garibaldi, near Squamish B.C., is one of Canada's tallest (2,678 m) and most recently active volcanoes. [SE photo] The volcanic peak in the centre is Mt. Price and the dark flat–topped peak is The Table. All three of these volcanoes were active during the last glaciation. Mt. Garibaldi last erupted approximately 10,000 years ago.* © Steven Earle. CC BY

The study of volcanoes is critical to our understanding of the geological evolution of Earth, and to our understanding of significant changes in climate. But, most important of all, understanding volcanic eruptions allows us to save lives and property. Over the past few decades, volcanologists have made great strides in their ability to forecast volcanic eruptions and predict the consequences — this has already saved thousands of lives.

The largest eruptions can literally explode a volcanic mountain, ejecting immense quantities of material into the environment and causing enormous damage and loss of life. For example, an eruption of Mount Vesuvius in the year 79 CE (Common Era) buried the Roman city of Pompeii, killing almost all of its inhabitants. A 1902 explosion of Mont Pelée on the Caribbean island of Martinique killed 30,000 people. Another famous Indonesian eruption was that of Krakatau in the Sunda Strait in 1883, which ejected 18-21 km^3 of material as high as 50-80 km into the atmosphere. The 30-m tsunami associated with this eruption killed about 36,000 people in coastal villages.

The greatest eruption of modern times was that of Tambora, a volcano in Indonesia that exploded in 1815 and blew more than 300 km^3 of material into the atmosphere (including the top 1,300 m of the mountain). Some of the finer particulates of this massive eruption were blown into the upper atmosphere (the stratosphere), causing an increase in Earth's reflectivity that resulted in global cooling. The year 1816 became known as the "year without a summer" in Europe and North America because of its unusually cool and wet weather, including frost and snowfall during the summer months.

Large volcanic eruptions can also disturb great expanses of forest and other ecosystems. For instance, the 1980 explosion of Mount St. Helen's in the state of Washington blew down about 21,000 hectares of coniferous forest and otherwise damaged another 40,000 ha. Mudslides also devastated large areas, and a vast region was covered by particulate debris (known as tephra) that settled from the atmosphere.

Some volcanoes produce chronic lava flows and venting of gases. These volcanoes tend to form distinctive, cone-shaped mountains from their accumulated lava, which solidifies into finely crystalline, glassy rocks. An active example of this spectacular process is Mount Kilauea in Hawaii, which sometimes erupts continuously for years. The slowly flowing lava from these volcanoes can destroy buildings and vegetation but is not otherwise dangerous because people and animals can avoid the molten streams.

Types of Volcanoes

Volcanoes can be classified according to the type and form of their ejecta. The basic types are: composite volcanoes, shield volcanoes, cinder cones, and lava domes. **Composite volcanoes** are steep-sided, symmetrical cones built of multiple layers of viscous lava and ash. Most composite volcanoes have a crater at the summit which contains the central vent. Lavas flow from

breaks in the crater wall or from cracks on the flanks of the cone. Mt Fuji in Japan and Mt Ranier in Washington are examples of composite volcanoes.

Shield volcanoes are built almost entirely of highly fluid (low viscosity) lava flows. They form slowly from numerous flows that spread out over a wide area from a central vent. The resultant structure is a broad, gently sloping cone with a profile like a warrior's shield. Mt Kilauea in Hawaii is an example of a shield volcano.

Cinder cones are the simplest type of volcano. They form when lava blown violently into the area breaks into small fragments that solidify and fall as cinders. A steep-sided cone shape is formed around the vent, with a crater at the summit. Sunset Crater in Arizona is a cinder cone that formed less than a thousand years ago, disrupting the lives of the native inhabitants of the region.

Lava domes are formed when highly viscous lava is extruded from a vent and forms a rounded, steep-sided dome. The lava piles up around and on the vent instead of flowing away, mostly growing by expansion from within. Lava domes commonly occur within the craters or on the flanks of composite volcanoes.

Volcanic Hazards

There are two classes of volcanic hazards, direct and indirect. Direct hazards are forces that directly kill or injure people, or destroy property or wildlife habitat. Indirect hazards are volcanism-induced environmental changes that lead to distress, famine, or habitat degradation. It is estimated that indirect effects of volcanism have accounted for approximately 8 million deaths during historical times, while direct effects have accounted for fewer than 200,000, or 2.5% of the total. Some of the more important types of volcanic hazards are summarized in Table 12.3.1.

Table 12.3.1 A summary of the important volcanic hazards

[Skip Table]

Type	Description	Risk
Tephra emissions	Small particles of volcanic rock emitted into the atmosphere	• Respiration problems for some individuals • Significant climate cooling leading to crop failure and famine • Damage to aircraft
Gas emissions	The emission of gases before, during, and after an eruption	• Climate cooling leading to crop failure and famine • In some cases, widespread poisoning
Pyroclastic density current	A very hot (several 100°C) mixture of gases and volcanic fragments (tephra) that flows rapidly (up to 100s of kilometers per hour (km/h)) down the side of a volcano	Extreme hazard — destroys anything in the way
Pyroclastic fall	Vertical fall of tephra in the area surrounding an eruption	• Thick tephra coverage of areas close to the eruption (1 km to 10s of kilometers) • Collapsed roofs
Lahar	A flow of mud and debris down a channel leading away from a volcano, triggered either by an eruption or a severe rain event	Severe risk of destruction for anything within the channel—lahar mud flows can move at 10s of km/h
Sector collapse/ debris avalanche	The failure of part of a volcano, either due to an eruption or for some other reason, leading to the failure of a large portion of the volcano	Severe risk of destruction for anything in the path of the debris avalanche
Lava flow	The flow of lava away from a volcanic vent	People and infrastructure at risk, but lava flows tend to be slow (less than km/h) and are relatively easy to avoid

Volcanic Gas and Tephra Emissions

Large volumes of **tephra** (rock fragments, mostly **pumice**) and gases are emitted during major **plinian eruptions** (large explosive eruptions with hot gas and tephra columns extending into the stratosphere) at composite volcanoes, and a large volume of gas is released during some very high-volume effusive eruptions. One of the major effects is cooling of the climate by 1° to 2°C for several months to a few years because the dust particles and tiny droplets and particles of sulfur compounds block the sun. The last significant event of this type was in 1991 and 1992 following the large eruption of Mount Pinatubo in the Philippines. A temperature decrease of 1° to 2°C may not seem like very much, but that is the global average amount of cooling, and cooling was much more severe in some regions and at some times.

Over an eight-month period in 1783 and 1784, a massive effusive eruption took place at the Laki volcano in Iceland. Although there was relatively little volcanic ash involved, a massive amount of sulfur dioxide was released into the atmosphere, along with a significant volume of hydrofluoric acid (HF). The sulphate **aerosols** that formed in the atmosphere led to dramatic cooling in the northern hemisphere. There were serious crop failures in Europe and North America, and a total of 6 million people are estimated to have died from famine and respiratory complications. In Iceland, poisoning from the HF resulted in the death of 80% of sheep, 50% of cattle, and the ensuing famine, along with HF poisoning, resulted in more than 10,000 human deaths—about 25% of the population.

Volcanic ash can also have serious implications for aircraft because it can destroy jet engines. For example, over 5 million airline passengers had their travel disrupted by the 2010 Eyjafjallajökull volcanic eruption in Iceland.

Pyroclastic Density Currents

In a typical explosive eruption at a composite volcano, the tephra and gases are ejected with explosive force and are hot enough to be forced high up into the atmosphere. As the eruption proceeds, and the amount of gas in the rising magma starts to decrease, parts will become heavier than air, and they can then flow downward along the flanks of the volcano (Figure 12.3.2). As they descend, they cool more and flow faster, reaching speeds up to several hundred kilometers per hour. A **pyroclastic density current** (PDC) consists of tephra ranging in size from boulders to microscopic shards of glass (made up of the edges and junctions of the bubbles of shattered pumice), plus gases (dominated by water vapor, but also including other gases). The temperature of this material can be as high as 1000°C. Among the most famous PDCs are the one that destroyed Pompeii in the year 79 CE, killing an estimated 18,000 people, and the one that destroyed the town of St. Pierre, Martinique, in 1902, killing an estimated 30,000.

The buoyant upper parts of pyroclastic density currents can flow over water, in some cases for several kilometers. The 1902 St. Pierre PDC flowed out into the city's harbour and destroyed several wooden ships anchored there.



Figure 12.3.2 The plinian eruption of Mount Mayon, Philippines. in 1984. Although most of the eruption column is ascending into the atmosphere, there are pyroclastic density currents flowing down the sides of the volcano in several places.
Source: "Pyroclastic flows at Mayon Volcano" by USGS. Public domain.

Pyroclastic Fall

Most of the tephra from an explosive eruption ascends high into the atmosphere, and some of it is distributed around Earth by high-altitude winds. The larger components (larger than 0.1 mm) tend to fall relatively close to the volcano, and the amount produced by large eruptions can cause serious damage and casualties. The large 1991 eruption of Mount Pinatubo in the Philippines resulted in the accumulation of tens of centimeters of ash in fields and on rooftops in the surrounding populated region. Heavy typhoon rains that hit the island at the same time added to the weight of the tephra, leading to the collapse of thousands of roofs and to at least 300 of the 700 deaths attributed to the eruption.

Lahar

A **lahar** is any mudflow or **debris flow** that is related to a volcano. Most are caused by melting snow and ice during an eruption, as was the case with the lahar that destroyed the Colombian town of Armero in 1985 (described earlier). Lahars can also happen when there is no volcanic eruption, and one of the reasons is that, as we've seen, composite volcanoes tend to be weak and easily eroded.

In October 1998, category 5 hurricane Mitch slammed into the coast of central America. Damage was extensive and 19,000 people died, not so much because of high winds but because of intense rainfall—some regions received almost 2 m of rain over a few days! Mudflows and debris flows occurred in many areas, especially in Honduras and Nicaragua. An example is at the Casita Volcano in Nicaragua, where the heavy rains weakened rock and volcanic debris on the upper slopes, resulting in a debris flow that rapidly built in volume as it raced down the steep slope, and then ripped through the towns of El Porvenir and Rolando Rodriguez

killing more than 2,000 people (Figure 12.3.3). El Porvenir and Rolando Rodriguez were new towns that had been built without planning approval in an area that was known to be at risk of lahars.



Figure 12.3.3 Part of the path of the lahar from Casita Volcano, October 30, 1998.
Source: "Casita Volcano" by USGS. Public domain.

Sector Collapse and Debris Avalanche

In the context of volcanoes, **sector collapse** or flank collapse is the catastrophic failure of a significant part of an existing volcano, creating a large debris avalanche. This hazard was first recognized with the failure of the north side of Mount St. Helens immediately prior to the large eruption on May 18, 1980. In the weeks before the eruption a large bulge had formed on the side of the volcano, the result of magma transfer from depth into a satellite magma body within the mountain itself. Early on the morning of May 18, a moderate earthquake struck nearby; this is thought to have destabilized the bulge, leading to Earth's largest ever observed slope failure. The failure of this part of the volcano exposed the underlying satellite magma chamber, causing it to explode sideways, which then exposed the conduit leading to the magma chamber below. The resulting plinian eruption—with a 24 kilometre high eruption column—lasted for nine hours.

In August 2010, a massive part of the flank of B.C.'s Mount Meager gave way and about 48 million cubic meters (m^3) of rock rushed down the valley, one of the largest slope failures in Canada in historical times. More than 25 slope failures have taken place at Mount Meager in the past 8,000 years, some of them more than 10 times larger than the 2010 failure.

Lava Flows

Lava flows at volcanoes like Kilauea do not advance very quickly, and in most cases, people can get out of the way. Of course, it is more difficult to move infrastructure, and so buildings and roads are typically the main casualties of lava flows.

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12.4: Mass Wasting

Early in the morning on January 9, 1965, 47 million cubic metres of rock broke away from the steep upper slopes of Johnson Peak (16 km southeast of Hope) and roared 2,000 m down the mountain, gouging out the contents of a small lake at the bottom, and continuing a few hundred metres up the other side (Figure 15.1). Four people, who had been stopped on the highway by a snow avalanche, were killed. Many more might have become victims, except that a Greyhound bus driver, en route to Vancouver, turned his bus around on seeing the avalanche. The rock failed along weakened foliation planes of the metamorphic rock on Johnson Peak, in an area that had been eroded into a steep slope by glacial ice. There is no evidence that it was triggered by any specific event, and there was no warning that it was about to happen. Even if there had been warning, nothing could have been done to prevent it. There are hundreds of similar situations throughout British Columbia.



Figure 12.4.1: The site of the 1965 Hope Slide as seen in 2014. The initial failure is thought to have taken place along the foliation planes and sill within the area shown in the inset. © Steven Earle. CC BY

What can we learn from the Hope Slide? In general, we cannot prevent most mass wasting, and significant effort is required if an event is to be predicted with any level of certainty. Understanding the geology is critical to understanding mass wasting. Although failures are inevitable in a region with steep slopes, larger ones happen less frequently than smaller ones, and the consequences vary depending on the downslope conditions, such as the presence of people, buildings, roads, or fish-bearing streams.

An important reason for learning about mass wasting is to understand the nature of the materials that fail, and how and why they fail so that we can minimize risks from similar events in the future. For this reason, we need to be able to classify mass-wasting events, and we need to know the terms that geologists, engineers, and others use to communicate about them.

Landslides and Mass wasting, which is synonymous with “slope failure,” is the failure and downslope movement of rock or unconsolidated materials in response to gravity. The term “landslide” is almost synonymous with mass wasting, but not quite, because some people reserve “landslide” for relatively rapid slope failures, while others do not.

Classification of Mass Wasting Events

It’s important to classify slope failures so that we can understand what causes them and learn how to mitigate their effects. The three criteria used to describe slope failures are:

- The type of material that failed (typically either bedrock or unconsolidated sediment)
- The mechanism of the failure (how the material moved)
- The rate at which it moved

The type of motion is the most important characteristic of a slope failure, and there are three different types of motion:

- If the material drops through the air, vertically or nearly vertically, it’s known as a **fall**.

- If the material moves as a mass along a sloping surface (without internal motion within the mass), it's a **slide.**
- If the material has internal motion, like a fluid, it's a **flow**.

Unfortunately it's not normally that simple. Many slope failures involve two of these types of motion, some involve all three, and in many cases, it's not easy to tell how the material moved. The types of slope failure that we'll cover here are summarized in Table 12.4.1.

Table 12.4.1: Classification of slope failures based on type of material and type of motion

[Skip Table]

Failure Type	Type of Material	Type of Motion	Rate of Motion
Rock fall	Rock fragments	Vertical or near-vertical fall (plus bouncing in many cases)	Very fast (Greater than 10s of meters per second)
Rock slide	A large rock body	Motion as a unit along a planar surface (translational sliding)	Typically very slow (millimeters per year to centimeters per year), but some can be faster
Rock avalanche	A large rock body that slides and then breaks into small fragments	Flow (at high speeds the mass of rock fragments is suspended on a cushion of air)	Very fast (Greater than tens of meters per second)
Creep or solifluction	Soil or other overburden; in some cases, mixed with ice	Flow (although sliding motion may also occur)	Very slow (millimeters per year to centimeters per year)
Slump	Thick deposits (a metre to 10s of meters) of unconsolidated sediment	Motion as a unit along a curved surface (rotational sliding)	Slow (centimeters per year to meters per year)
Mudflow	Loose sediment with a significant component of silt and clay	Flow (a mixture of sediment and water moves down a channel)	Moderate to fast (centimeters per second to meters per second)
Debris flow	Sand, gravel, and larger fragments	Flow (similar to a mudflow, but typically faster)	Fast (meters per second)

Rock Fall

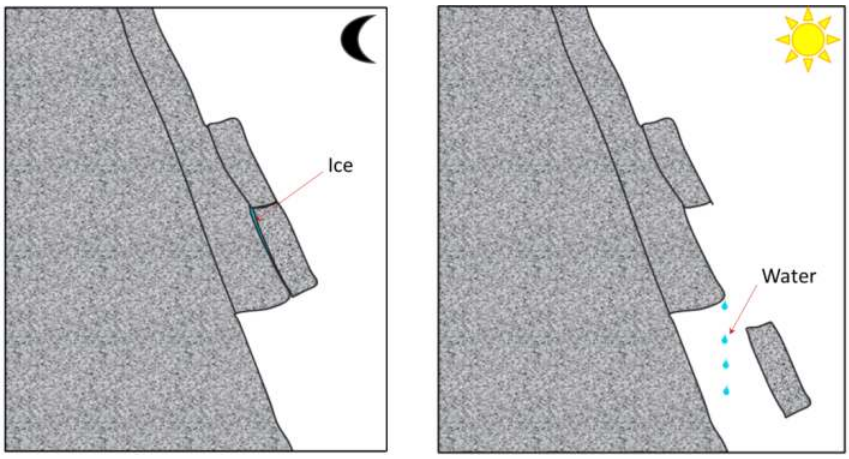


Figure 12.4.2 The contribution of freeze-thaw to rock fall. © Steven Earle. CC BY

Rock fragments can break off relatively easily from steep bedrock slopes, most commonly due to frost-wedging in areas where there are many freeze-thaw cycles per year. If you've ever hiked along a steep mountain trail on a cool morning, you might have heard the occasional fall of rock fragments onto a **talus slope**. This happens because the water between cracks freezes and expands

overnight, and then when that same water thaws in the morning sun, the fragments that had been pushed beyond their limit by the ice fall to the slope below (Figure 12.4.2).

A typical talus slope, near Keremeos in southern B.C., is shown in Figure 12.4.3. In December 2014, a large block of rock split away from a cliff in this same area. It broke into smaller pieces that tumbled down the slope and crashed into the road, smashing the concrete barriers and gouging out large parts of the pavement. Luckily no one was hurt.



Figure 12.4.3 Left: A talus slope near Keremeos, B.C., formed by rock fall from the cliffs above. Right: The results of a rock fall onto a highway west of Keremeos in December 2014. © Steven Earle. CC BY

Rock Slide

A rock slide is the sliding motion of rock along a sloping surface. In most cases, the movement is parallel to a fracture, bedding, or metamorphic foliation plane, and it can range from very slow to moderately fast. The word **sackung** describes the very slow motion of a block of rock (millimeters per year to centimeters per year) on a slope. A good example is the Downie Slide north of Revelstoke, B.C., which is shown in Figure 12.4.4. In this case, a massive body of rock is very slowly sliding down a steep slope along a plane of weakness that is approximately parallel to the slope. The Downie Slide, which was first recognized in the 1950s, prior to the construction of the Revelstoke Dam in the late 1970s, was moving very slowly at the time (a few centimeters per year). Geological engineers were concerned that the presence of water in the reservoir (visible in Figure 12.4.4) could further weaken the plane of failure, leading to an acceleration of the motion. The result would have been a catastrophic failure into the reservoir that would have sent a wall of water over the dam and into the community of Revelstoke. During the construction of the dam they tunneled into the rock at the base of the slide and drilled hundreds of drainage holes upward into the plane of failure. This allowed water to drain out so that the pressure was reduced, which reduced the rate of movement of the sliding block. BC Hydro monitors this site continuously; the slide block is currently moving more slowly than it was prior to the construction of the dam.

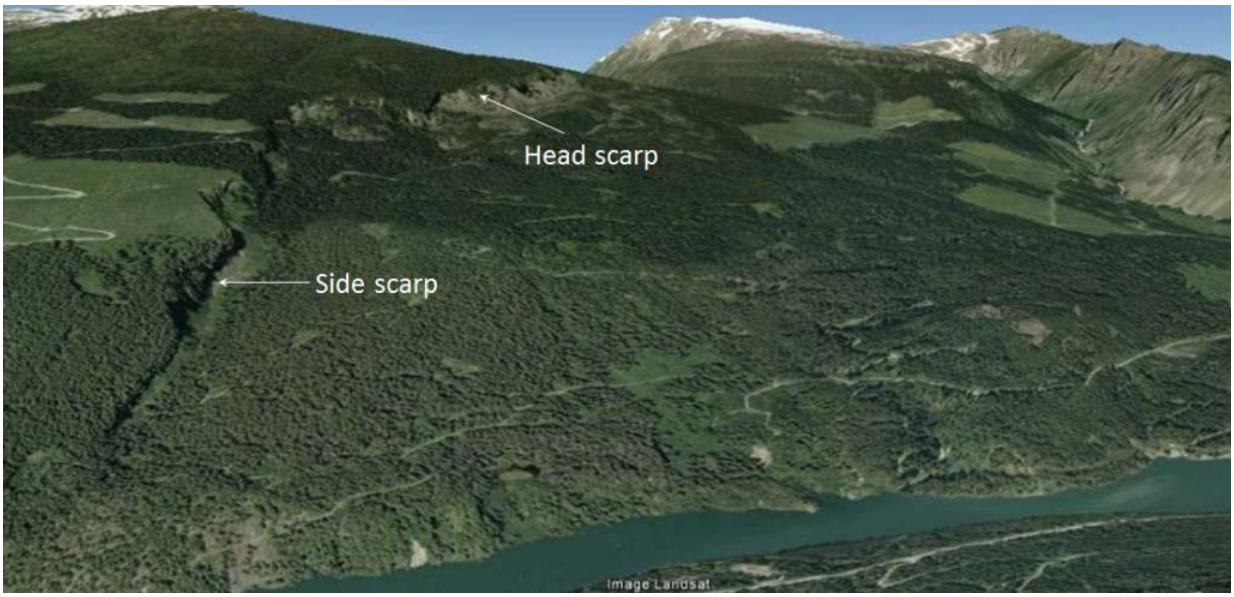


Figure 12.4.4 The Downie Slide, a sackung, on the shore of the Revelstoke Reservoir (above the Revelstoke Dam). The head scarp is visible at the top and a side-scarp along the left side. © Google Earth. Used with permission for non-commerical purposes.



Figure 12.4.5 Site of the 2008 rock slide at Porteau Cove. Notice the prominent fracture set parallel to the surface of the slope. The slope has been stabilized with rock bolts (visible near to the top of the photo) and holes have been drilled into the rock to improve drainage (one is visible in the lower right). Risk to passing vehicles from rock fall has been reduced by hanging mesh curtains (background). © Steven Earle. CC BY Photo 2012

In the summer of 2008, a large block of rock slid rapidly from a steep slope above Highway 99 near Porteau Cove (between Horseshoe Bay and Squamish). The block slammed into the highway and adjacent railway and broke into many pieces. The highway was closed for several days, and the slope was subsequently stabilized with rock bolts and drainage holes. As shown in Figure 12.4.5, the rock is fractured parallel to the slope, and this almost certainly contributed to the failure. However, it is not actually known what triggered this event as the weather was dry and warm during the preceding weeks, and there was no significant earthquake in the region.



Figure 12.4.6 The August 2010 Mount Meager rock avalanche, showing where the slide originated (red arrow, 4 km upstream) and its path down a steep narrow valley. The yellow arrows show how far up the valley the avalanche extended. “2010 Mt. Meager rock avalanche” © Isaac Earle. CC BY.

If a rock slides and then starts moving quickly (meters per second), the rock is likely to break into many small pieces, and at that point it turns into a **rock avalanche**, in which the large and small fragments of rock move in a fluid manner supported by a cushion of air within and beneath the moving mass. The 1965 Hope Slide (Figure 12.4.1) was a rock avalanche, as was the famous 1903 Frank Slide in southwestern Alberta. The 2010 slide at Mount Meager (west of Lillooet) was also a rock avalanche, and rivals the Hope Slide as the largest slope failure in Canada during historical times (Figure 12.4.6).

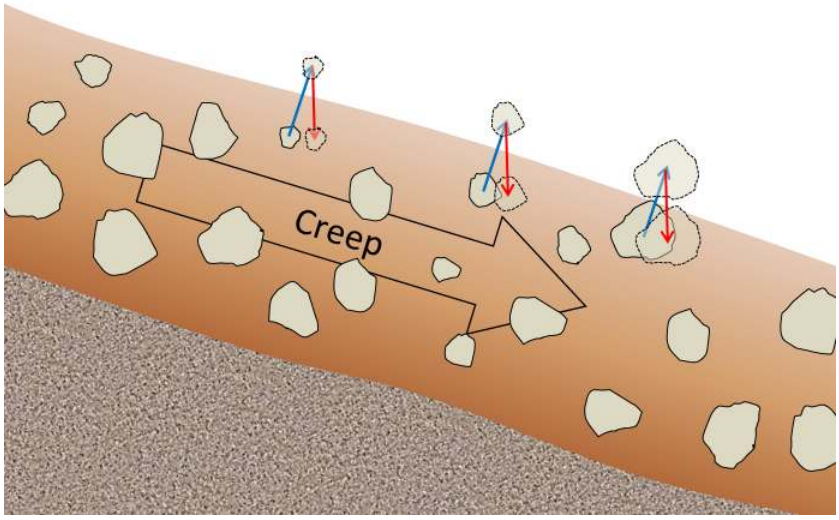


Figure 12.4.7 A depiction of the contribution of freeze-thaw to creep. The blue arrows represent uplift caused by freezing in the wet soil underneath, while the red arrows represent depression by gravity during thawing. The uplift is perpendicular to the slope, while the drop is vertical. © Steven Earle. CC BY.

The very slow—millimeters per year to centimeters per year—movement of soil or other unconsolidated material on a slope is known as creep. **Creep**, which normally only affects the upper several centimeters of loose material, is typically a type of very slow flow, but in some cases, sliding may take place. Creep can be facilitated by freezing and thawing because, as shown in Figure 12.4.7, particles are lifted perpendicular to the surface by the growth of ice crystals within the soil, and then let down vertically by gravity when the ice melts. The same effect can be produced by frequent wetting and drying of the soil. In cold environments, **solifluction** is a more intense form of freeze-thaw-triggered creep.

Creep is most noticeable on moderate-to-steep slopes where trees, fence posts, or grave markers are consistently leaning in a downhill direction. In the case of trees, they try to correct their lean by growing upright, and this leads to a curved lower trunk known as a “pistol butt.” An example is shown on Figure 12.4.8.



Figure 12.4.8 Pistol-butt shaped trees on a slope that is experiencing creep © Steven Earle. CC BY.

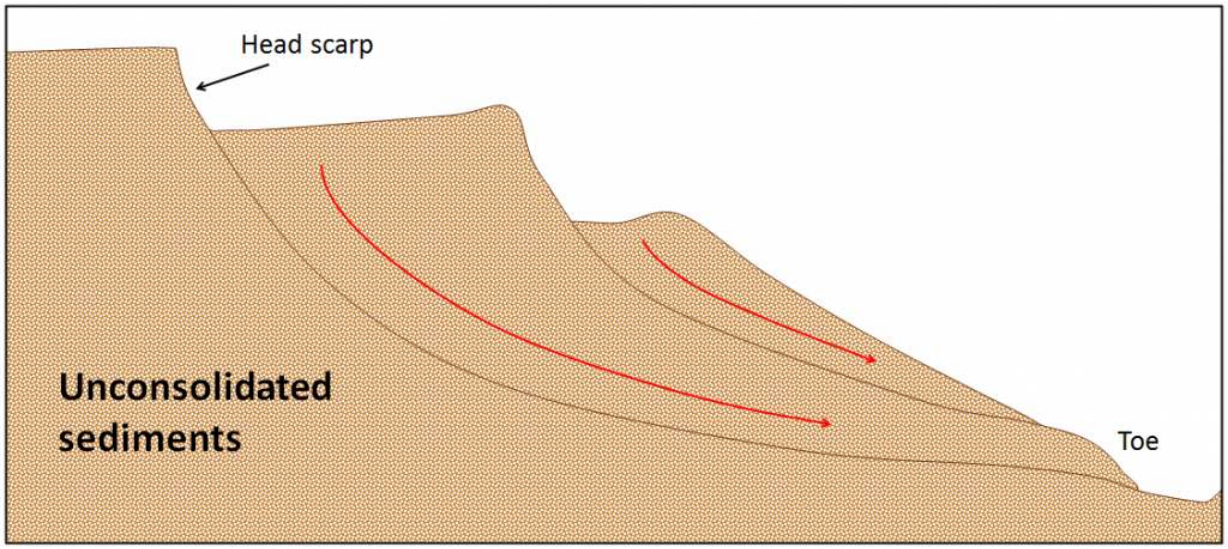


Figure 12.4.9 A depiction of the motion of unconsolidated sediments in an area of slumping. © Steven Earle. CC BY.

Slump is a type of slide (movement as a mass) that takes place within thick unconsolidated deposits (typically thicker than 10 meters). Slumps involve movement along one or more curved failure surfaces, with downward motion near the top and outward motion toward the bottom (Figure 12.4.9). They are typically caused by an excess of water within these materials on a steep slope.



Figure 12.4.10 A slump along the banks of a small coulee near Lethbridge, Alberta. The main head-scarp is clearly visible at the top, and a second smaller one is visible about one-quarter of the way down. The toe of the slump is being eroded by the seasonal stream that created the coulee. © Steven Earle. CC BY. Photo 2005

An example of a slump in the Lethbridge area of Alberta is shown in Figure 12.4.10. This feature has likely been active for many decades, and moves a little more whenever there are heavy spring rains and significant snowmelt runoff. The toe of the slump is failing because it has been eroded by the small stream at the bottom.

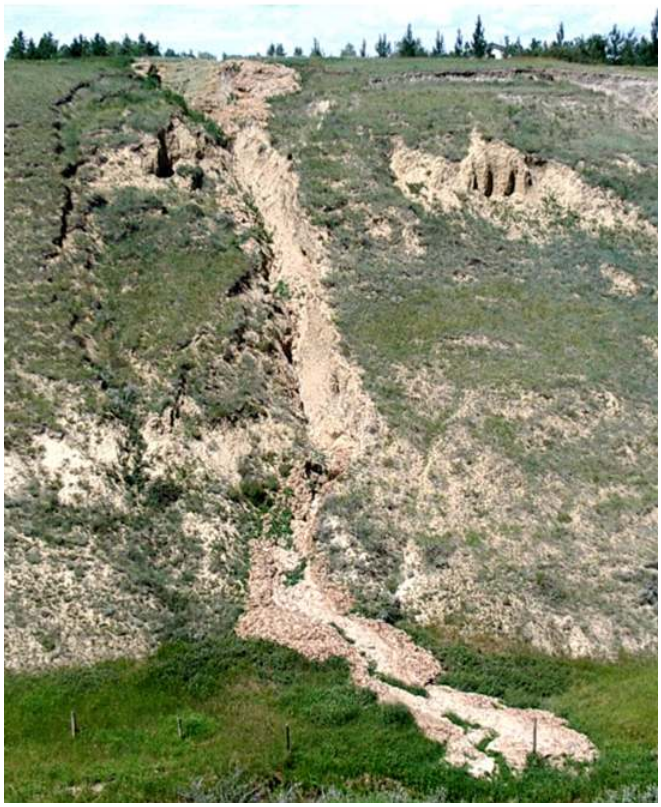


Figure 12.4.11 A slump (left) and an associated mudflow (centre) at the same location as Figure 12.4.10, near Lethbridge, Alberta. © Steven Earle. CC BY.

When a mass of sediment becomes completely saturated with water, the mass loses strength, to the extent that the grains are pushed apart, and it will flow, even on a gentle slope. This can happen during rapid spring snowmelt or heavy rains, and is also relatively common during volcanic eruptions because of the rapid melting of snow and ice. (A mudflow or debris flow on a volcano or during a volcanic eruption is a *lahar*.) If the material involved is primarily sand-sized or smaller, it is known as a mudflow, such as the one shown in Figure 12.4.11.

If the material involved is gravel sized or larger, it is known as a debris flow. Because it takes more gravitational energy to move larger particles, a debris flow typically forms in an area with steeper slopes and more water than does a mudflow. In many cases, a debris flow takes place within a steep stream channel, and is triggered by the collapse of bank material into the stream. This creates a temporary dam, and then a major flow of water and debris when the dam breaks. This is the situation that led to the fatal debris flow at Johnsons Landing, B.C., in 2012. A typical west-coast debris flow is shown in Figure 12.4.12. This event took place in November 2006 in response to very heavy rainfall. There was enough energy to move large boulders and to knock over large trees.



Figure 12.4.12 The lower part of debris flow within a steep stream channel near Buttle Lake, B.C., in November 2006. © Steven Earle. CC BY.

Mass-Wasting Triggers

In the previous section, we talked about the shear force and the shear strength of materials on slopes, and about factors that can reduce the shear strength. Shear force is primarily related to slope angle, and this does not change quickly. But shear strength can change quickly for a variety of reasons, and events that lead to a rapid reduction in shear strength are considered to be **triggers** for mass wasting.

An increase in water content is the most common mass-wasting trigger. This can result from rapid melting of snow or ice, heavy rain, or some type of event that changes the pattern of water flow on the surface. Rapid melting can be caused by a dramatic increase in temperature (e.g., in spring or early summer) or by a volcanic eruption. Heavy rains are typically related to major storms. Changes in water flow patterns can be caused by earthquakes, previous slope failures that dam up streams, or human structures that interfere with runoff (e.g., buildings, roads, or parking lots). An example of this is the deadly January 2005 debris flow in North Vancouver in the Riverside Drive area. The debris flow happened during a rainy period, but was likely triggered by excess runoff related to the roads at the top of this slope and by landscape features, including a pool. The 2005 failure took place in an area that had failed previously, and a report written in 1980 recommended that the municipal authorities and residents take steps to address surface and slope drainage issues. Little was done to improve the situation.

In some cases, a *decrease* in water content can lead to failure. This is most common with clean sand deposits (e.g., the upper layer in Figure 12.4.15 (left)), which lose strength when there is no water to hold the grains together.

Freezing and thawing can also trigger some forms of mass wasting. More specifically, the thawing can release a block of rock that was attached to a slope by a film of ice.

One other process that can weaken a body of rock or sediment is shaking. The most obvious source of shaking is an earthquake, but shaking from highway traffic, construction, or mining will also do the job. Several deadly mass-wasting events (including snow avalanches) were triggered by the M7.8 earthquake in Nepal in April 2015.

Saturation with water and then seismic shaking led to the occurrence of thousands of slope failures in the Sapporo area of Hokkaido, Japan in September 2018, as shown on Figure 12.4.18. The area was drenched with rain from tropical storm Jebi on September 4th. On September 6th it was shaken by a M6.6 earthquake which triggered debris flows in the water-saturated volcanic materials on steep slopes. There were 41 deaths related to the slope failures.



Figure 12.4.18 Slope failures in the Sapporo area of Japan following a typhoon (Sept. 4th, 2018) and earthquake (Sept. 6th, 2018) (Before and after Landsat 8 images: top: July 2017, bottom: September 2018). Source: "Landslides in Hokkaido" by Lauren Dauphin, NASA Earth Observatory. Public domain.

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12.5: Floods

The Definition of a Flood

Here's a simple definition of a river flood: *the occurrence of a flow of such magnitude that it overtops the natural or artificial banks in a reach of river channel*. If a floodplain exists, here's another way of defining a flood: *any flow that spreads out over the floodplain*.

The *relative* volume of flood water is not large: on average, water discharged in excess of channel capacity constitutes about 5% of the total annual discharge of the given drainage basin. But the *absolute* volume of flood water is staggering. Hypothetical example: a two-inch rainstorm over a one-square-mile catchment the soils of which can absorb 0.5 inches would supply almost 3.5 million cubic feet of water is a couple of hours! (That's a cube 150 feet on a side.)

A flood is a *wave*: it has a wavelike shape (although very subdued, with low amplitude relative to wavelength), and it propagates downriver at some speed, typically less than the mean velocity of flow of water in the river.

Floodplains

Here are two similar but not quite identical definitions of a floodplain, taken from the literature:

- the flat area adjacent to the river channel, constructed by the present river in the present climate and frequently subjected to overflow (Leopold, 1994)
- the flat area adjoining a river channel constructed by the river in the present climate and overflowed at times of high discharge (Dunne and Leopold, 1978)

The existence of a floodplain is testimony to the lateral migration of the river channel. With time, the shifting channel sweeps the entire width of the floodplain, eroding the "front" bank and depositing the "rear" bank as it goes (Figure $12.5.1-2$). If the climate, or the base level, changes in such a way that the river degrades (i.e., lowers its bed), the old floodplain is incised, forming a set of terraces, and a new, narrower floodplain develops. If the climate, or the base level, changes in such a way that the river aggrades, the floodplain typically (except in extreme cases) aggrades along with it.



Figure 12.5.1**:** Top: *The meandering channel of the Bonnell Creek, Nanoose, B.C. The stream is flowing toward the viewer. The sand and gravel point bar must have formed when the creek was higher and the flow faster than it was when the photo was taken.* © Steven Earle. CC BY.



Figure 12.5.2**:** *The meandering channel of the Nowitna River, Alaska. Numerous oxbow lakes are present and another meander cutoff will soon take place. [Oliver Kumis, http://commons.wikimedia.org/wiki/Fi...tna_river.jpg]*

What determines the height of the floodplain above the channel bed? That has to do with the relationship between *effectiveness* and *frequency*. Low discharges are common but not effective in sediment transport and channel shaping, whereas very high discharges are very effective at transporting sediment but very uncommon. The discharges with greatest effectiveness in maintaining channel and floodplain geometry are at some intermediate value: high but not extremely high, and common but not extremely common. For most rivers, bank-full discharges (those that spill over onto the floodplain) occur once or twice a year, on average. (It turns out that the discharge that is responsible for the maximum sediment discharge, in a given time period like a year, called the ***effective discharge,*** is very close to being equal to the ***bank-full discharge***.)

What are floodplains like?

- They range in width from several meters, on the smallest streams, to many tens of kilometers, on the largest rivers.
- They are not flat as a board: they have minor relief, in the form of sloughs and depressions left behind by the irregular shifting of the river channel.
- They are developed in their classic sense in connection with meandering rivers. Braided rivers work irregularly across the entire valley, such that in a sense the entire valley is “river bed” (Figure 12.5.3).
- They are typically heavily vegetated in their natural state; in fact, the bank-stabilization effect of vegetation is one of the most important, if not *the* most important, factors in the existence of the floodplain in the first place.
- They vary in their “wetness”: usually they are dry and well above the local water table for most of the year, and are thus conducive to human use, but in areas with consistently high rainfall and/or strongly aggradational river regime ,there can be extensive swampy areas on the floodplain.



Figure 12.5.3**:** *Figure 13.19 The braided channel of the Kicking Horse River at Field, B.C.* © Steven Earle. CC BY.

Stream Erosion and Deposition

Flowing water is a very important mechanism for both erosion and deposition. Water flow in a stream is primarily related to the stream's gradient (slope or "steepness"), but it is also controlled by the geometry of the stream channel. As shown in Figure 12.5.4, water flow velocity is decreased by friction along the stream bed, so it is slowest at the bottom and edges and fastest near the surface and in the middle. In fact, the velocity just below the surface is typically a little higher than right at the surface because of friction between the water and the air. On a curved section of a stream, flow is fastest on the outside and slowest on the inside (Figure 12.5.1 *and* 12.5.4).

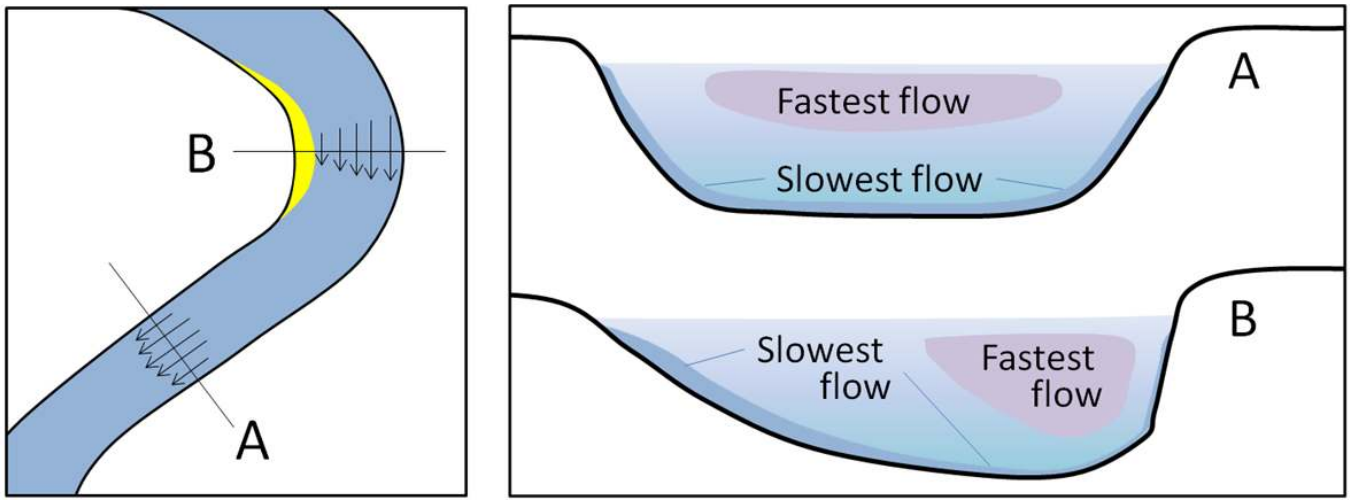


Figure 12.5.4: *The relative velocity of stream flow depending on whether the stream channel is straight or curved (left), and with respect to the water depth (right).* © Steven Earle. CC BY.

Other factors that affect stream-water velocity are the size of sediments on the stream bed — because large particles tend to slow the flow more than small ones — and the **discharge**, or volume of water passing a point in a unit of time (e.g., m^3/second). During a flood, the water level always rises, so there is more cross-sectional area for the water to flow in; however, as long as a river remains confined to its channel, the velocity of the water flow also increases.

Figure 12.5.5 shows the nature of sediment transportation in a stream. Large particles rest on the bottom — **bedload** — and may only be moved during rapid flows under flood conditions. They can be moved by **saltation** (bouncing) and by **traction** (being pushed along by the force of the flow). Smaller particles may rest on the bottom some of the time, where they can be moved by saltation and traction, but they can also be held in suspension in the flowing water, especially at higher velocities. The faster the water is flowing, the larger the particles that can be kept in suspension and transported within the flowing water. It is important to be aware that a stream can both erode and deposit sediments of different sizes at the same time.

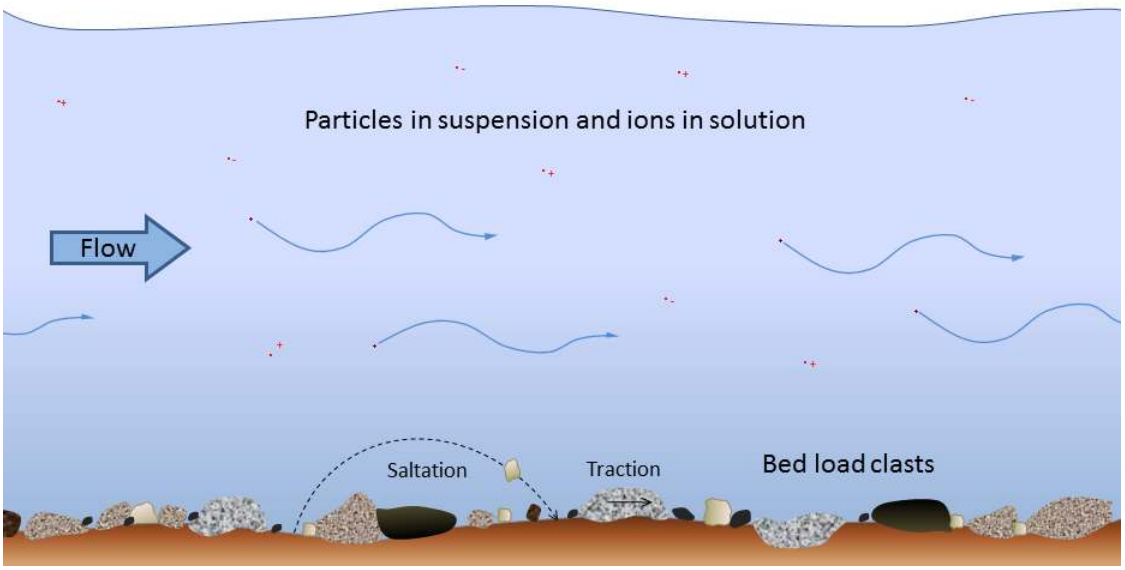


Figure \(\PageIndex{5}\): *Modes of transportation of sediments and dissolved ions (represented by red dots with + and – signs) in a stream.* © Steven Earle. CC BY.

As you know from intuition and from experience, streams that flow fast tend to be turbulent (flow paths are chaotic and the water surface appears rough) and the water may be muddy, while those that flow more slowly tend to have laminar flow (straight-line flow and a smooth water surface) and clear water. Turbulent flow is more effective than laminar flow at keeping sediments in suspension.

Stream water also has a dissolved load, which represents (on average) about 15% of the mass of material transported, and includes ions such as calcium (Ca^{+2}) and chloride (Cl-) in solution. The solubility of these ions is not affected by flow velocity.

A stream typically reaches its greatest velocity when it is close to flooding over its banks. This is known as the bank-full stage, as shown in Figure \(\PageIndex{6}\). As soon as the flooding stream overtops its banks and occupies the wide area of its flood plain, the water has a much larger area to flow through and the velocity drops significantly. At this point, sediment that was being carried by the high-velocity water is deposited near the edge of the channel, forming a natural bank or **levée**.

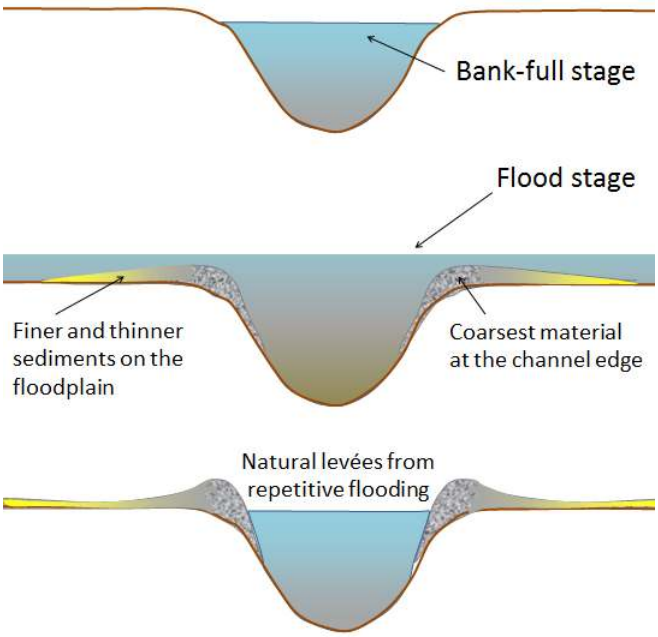


Figure \(\PageIndex{6}): *The development of natural levées during flooding of a stream. The sediments of the levée become increasingly fine away from the stream channel, and even finer sediments — clay, silt, and fine sand — are deposited across most of the flood plain.* © Steven Earle. CC BY.

Important Aspects of Floods

There are several important aspects of floods:

- ***discharge****:* discharge is important because of its close relation to flow velocity: how erosive is the flood flow in terms of banks, levees, and river structures?
- ***stage****:* the height of the water determines flood damage on the floodplain (This is what the public thinks about most in connection with floods.) Also, it relates to the water-passing capacity of bridges, culverts, dam spillways, etc.
- ***volume****:* this relates to how much water is available to be caught and impounded in reservoirs for water supply and flood control.
- ***area inundated****:* this is determined by stage together with river-valley topography.
- ***flow velocity****:* Although the flow velocity is much less over the floodplain than in the main channel, it can be great enough to cause damage.

What are the important effects or factors that govern the magnitude of a flood?

• **Rainfall** in the drainage basin upstream of the given point on the given river. This boils down to both rainfall *intensity* (depth per unit time) and rainfall *duration*, and also the *area* of the drainage basin covered by the rainstorm. The worst scenario is: high intensity for a long time over a large area of the drainage basin.

• Preceding condition of **soil moisture** in the area of rainfall: dry, which lessens the runoff, or saturated, which maximizes the runoff? The difference can be as much as half an inch of equivalent rainfall. That's a big effect for small floods but only a small effect for large floods.

• **Channel storage**. Think in terms of what happens when a flood discharge from an upstream river enters a large lake. The lake has a large surface area, so it takes a long time for the flood flow to raise the lake elevation and therefore increase the discharge out of the lake. This storage effect is also present to a non-negligible extent along the river channel itself: As the flood proceeds downstream, it has to fill a greater and greater volume of space in the river channel itself. This effect *attenuates* the flood in the downstream direction: in effect, it *stretches out* the hydrograph and lowers its peak (in terms of either the stage hydrograph or the discharge hydrograph).

• **Channel geometry**. The narrower the channel, for a given flood discharge, the more the stage rises. When the stage reaches bank-full, the water spreads out over the floodplain, and the stage then increases far less rapidly with increasing discharge.

Are Floods Getting Worse?

The answer to that question is certainly "yes", in terms of *dollar value of damage*, just because of greater human use of flood-prone areas near rivers. But the answer is yes also in terms of *higher stage*, because of the effect of more levee protection: the levees prevent the high discharges from spreading over the floodplain, so the rise in stage is confined to within the channel (Figure 12.5.7).



Figure 12.5.7: The stage of a flood flow for a given flood discharge. A) Before building of levees. B) After building of levees.

Is flood *discharge* increasing on average as well? There are two aspects to this question.

(1) In *urbanized* drainage basins, the percentage of area paved increases, thus decreasing the concentration time and tending to produce higher peaks in the hydrograph (stage and discharge) for a given rainfall. In rural drainage basins, bare-soil agriculture and clear cutting of forests have the same effect, although it seems not to be a really major effect. (Their effect on sediment yield is much greater, though.)

(2) Average rainfall in the drainage basin might be increasing because of *climate change* (although in much of the U.S., the prediction is that global warming will decrease precipitation rather than increase it). However, "storminess" (increased incidence of major rainstorms) is predicted to increase with climate change.

Can Floods Be Controlled?

A better way of putting the question would be: how can flood damage be minimized, in the sense that a given measure affords more flood protection than it costs to institute?

(1) *Build higher and higher levees*. Yes, you can keep the floodwaters off the floodplain by building the levees higher. In a real sense, however, this is a self-defeating activity (Figure 5-50). Under natural conditions, the flood stage has built into it an inherently self-limiting effect: the floodplain area is so much greater than the channel area that, once the river goes beyond bank-full to inundate the floodplain, water-level rise is minor. (But remember that "minor" in a natural sense may be catastrophic for people living on the floodplain.) Building the levees higher restricts the river discharge to a much narrower width of the river valley, so the flood stage is much higher than would have been the case without the higher levees. Because of the effect of eliminating the floodplain-spreading effect, effective protection would necessitate impractically high levees. Moreover, if those high levees are overtopped, the flood damage to the surrounding floodplain area is likely to be much worse than if the levees had not been there.

(2) *Flood-control dams*. Clearly, the stage and discharge hydrographs can be reduced downstream of a given point on a river by building a water-storage dam there: catch the water so as to knock down the flood peak, and release the water slowly later in times of lower discharge. The problems, aside from the great cost of building dams, is that the effect lessens downstream, so a number of dams are needed. For decades, in the mid-1900s, there was a controversy over whether to build lots of small dams in upstream areas or a few big dams in downstream areas. It was finally concluded that *for effective flood control throughout the whole basin, both sets of dams would be needed.*

(3) *Land management.* Good agricultural practices (fallow planting; terrace agriculture; contour planting) should increase infiltration and thus lower runoff, and also make the concentration time longer. Careful consideration has shown, however, that the effect is measured in tenths of an inch of equivalent rainfall, so it would be effective against minor floods but not major floods. The great benefit is greatly decreased soil erosion—which is a different (but very important) matter.

(4) *Restrictions on human use of floodplains*. Clearly the best way to prevent flood damage is not to put anything susceptible to damage on floodplains! The expense of relocation is usually too great for this to be practical (although it's happening in some places; it's a policy issue rather than a scientific issue), but intermediate measures are effective: establish floodways and spreading areas that are used for such things as agriculture (of certain kinds) and recreation, but not permanent structures. This doesn't solve the problem for already urbanized areas, though.

Can Floods Be Predicted?

Simple answer is just "no". Well, in a sense you *can* predict floods, but only after the rain has stopped falling! There are two aspects to this:

1. Given the rainstorm, predict the runoff in order to create a flood hydrograph
2. Given the flood hydrograph, watch the evolution of the hydrograph as the flood wave moves downstream. This technique is called ***flood routing***.

Various approximate techniques have been developed, and continue to be refined, for predicting the nature of the flood wave downstream of a rainstorm in a drainage basin. The assumptions and approximations are many: distribution of rainfall; extent of runoff vs. infiltration; time of concentration to create the hydrograph. It works okay for very small catchments but not so well for large catchments. It's a standard engineering technique for very small catchments (much less than one square mile). Once a flood is underway, however, there are good flood-routing techniques for predicting its future course down the river.

The other aspect of flood prediction has to do with the *statistics or probability of floods*. One assumes that, given the climate and the nature of the drainage basin upstream of a given point on a river, there is some underlying frequency distribution of floods, in terms of either stage or discharge. Any record of floods is then a sample population (in the parlance of statistics) from that underlying frequency distribution. So if you know the frequency distribution, you can give the probability of a given flood in a

given time period (that's not a prediction, but it's very useful in making a cost–benefit analysis or decision). However, the probability aspect of flood prediction assumes that the climate (specifically frequency of storms and average rainfall) and hydrology (partially controlled by development in the watershed) is not changing, which is not necessarily true with climate change or land use change. If you are interested in learning more about how fluvial hydrologists go about figuring out the probability of a given flood in a given time period in a given river system, go to the advanced topic at the end of this section.

Effects of Urbanization

Urbanization can have major effects of the magnitude and frequency of floods. Here's an example (Figure 12.5.8): Seneca Creek, near Rockville, Maryland, drains an area of 100 square miles. Its watershed has been subject to much urbanization in recent decades. Take the record of discharge, 61 years long, from 1931 to 1991, and divide it into two equal parts, early and late. The average annual flood in the period 1931–1960 was 3000 cfs, in the period 1961–1991 it was 6000 cfs—twice as great! Likewise, bank-full discharge occurred 1.2 times per year in first period but 2.2 times per year in second period.

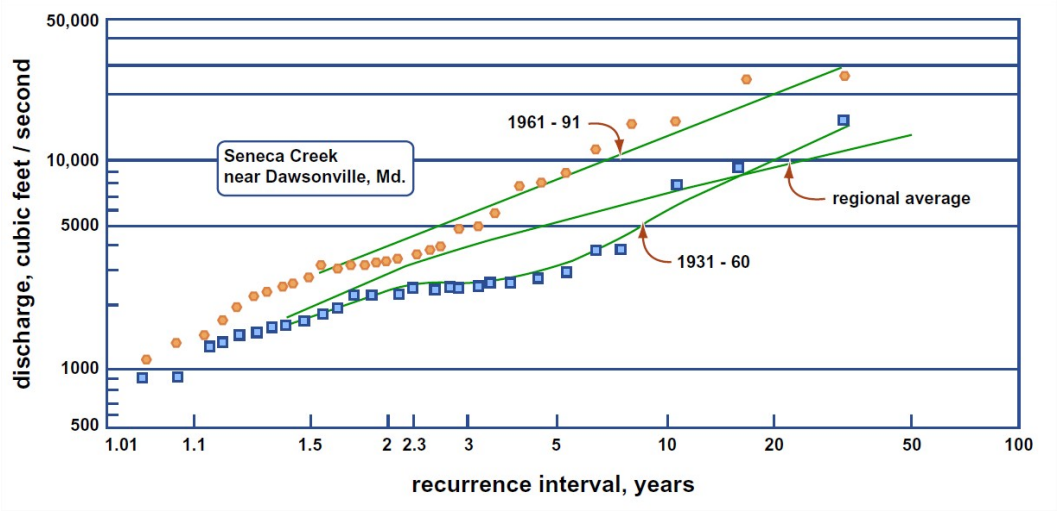


Figure 12.5.8: Flood-frequency curve for Seneca Creek, Maryland. (From Leopold, 1994)

Rainfall was almost exactly the same in the two periods, so the great differences have to be accounted for entirely by the effects of urbanization effects. The stream is not artificially leveed, so presumably the effect has been caused by a decrease in concentration time; the more pavement, the faster the runoff, and the shorter the concentration time.

Effects of Aggradation

There's a serious long-term problem in areas, especially in the lower reaches of large rivers, where crustal subsidence is non-negligible (i.e., the substrate beneath the active channel is moving downward relative to a datum like sea level) and/or where sea level itself is rising. (The former effect is more important than the latter.) The subsidence can be a combination of two effects:

- deep crustal subsidence
- subsidence caused by compaction of the sedimentary substrate of the river

The river channel aggrades to keep pace with subsidence, and in consequence it finds itself higher and higher above its floodplain—because, under conditions of net aggradation, deposition can be much faster in the channel, where the river is transporting most of its sediment, than over the floodplain. At certain times the river breaks through some particularly vulnerable point along its natural levees and finds its way out onto the floodplain, which is now at a significantly lower elevation, and establishes a whole new course for long distances down the floodplain. The process is called ***avulsion***; the river is said to ***avulse***. The river then proceeds to build up its channel bed and its levees, again to be high above the floodplain, and avulse once more. Avulsions often develop over a period of time rather than happening all at once: more and more of the river discharge is diverted through the gap in the levee, flood after flood. The end result, however, is the same.

To prevent avulsion, humans in avulsion-prone areas tend to build higher and higher levees, in the hope of preventing such an unfortunate event. The channel bed gets higher and higher relative to the surrounding floodplain (Figure 12.5.9).

This is happening today in the lowermost reaches of the Mississippi River. Much of the city of New Orleans lies well below the river. The Mississippi has an unfortunate preference for flowing down the Atchafalaya River to Morgan City. The U.S. Army Corps of Engineers maintains a gigantic headworks on the left bank of the river upstream of New Orleans to prevent the entire discharge of the Mississippi from going down the Atchafalaya; at present, about a third of the discharge leaves the Mississippi at that point. How long such a situation can be maintained is a matter of some controversy. If you would like to read an engaging account of the problem with the lower Mississippi, see the book by John McPhee (1989).

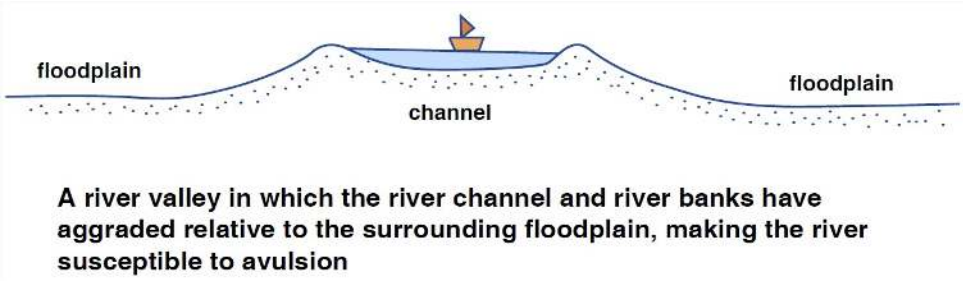


Figure 12.5.9: A river valley in which the river channel and river banks have aggraded relative to the surrounding floodplain, making the river susceptible to avulsion.

China has an even bigger problem with the Huang He (in English, the Yellow River), because they have been fighting the river for far longer than we have been fighting the Mississippi. The bed of the Huang He at the city of Kaifeng is almost fifteen meters above the streets of the city, only several kilometers from the river! The Chinese are working hard to come up with a way of solving this problem in the long term; for the near term (a few more decades) the levees are considered to be adequate.

Seasonality of River Discharge

The discharge levels of streams are highly variable depending on the time of year and on specific variations in the weather from one year to the next. In Canada, most streams show discharge variability similar to that of the Stikine River in northwestern B.C., as illustrated in Figure 12.5.10. The Stikine River has its lowest discharge levels in the depths of winter when freezing conditions persist throughout most of its drainage basin. Discharge starts to rise slowly in May, and then rises dramatically through the late spring and early summer as a winter's worth of snow melts. For the year shown, the minimum discharge on the Stikine River was 56 cubic meters per second (m^3/s) in March, and the maximum was 37 times higher, 2,470 m^3/s, in May.

Figure 12.5.10: Variations in discharge of the Stikine River during 2013.
© Steven Earle. CC BY. Based on from data at Water Survey of Canada, Environment Canada.

Streams in coastal areas of southern British Columbia show a very different pattern from those in most of the rest of the country because their drainage basins do not remain entirely frozen and because they receive a lot of rain (rather than snow) during the winter. The Qualicum River on Vancouver Island typically has its highest discharge levels in January or February and its lowest levels in late summer (Figure 12.5.11). In 2013, the minimum discharge was 1.6 m^3/s, in August, and the maximum was 34 times higher, 53 m^3/s, in March.

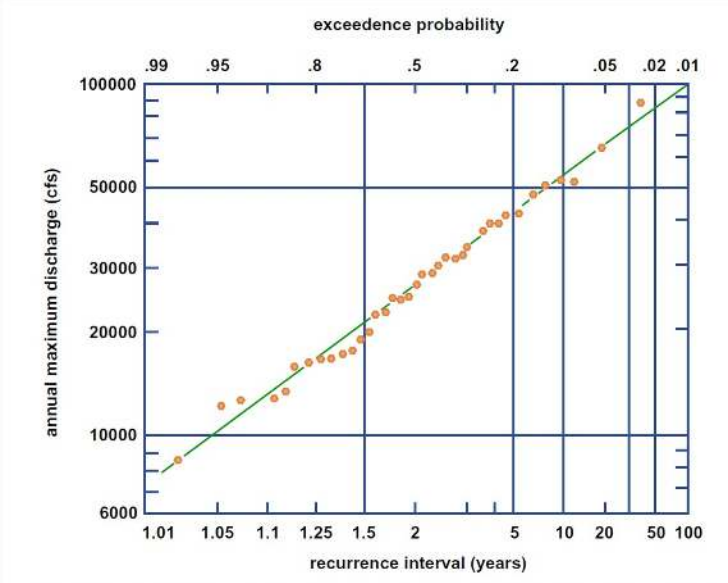
Figure 12.5.11: Variations in discharge of the Qualicum River during 2013.
© Steven Earle. CC BY. Based on from data at Water Survey of Canada, Environment Canada.

When a stream's discharge increases, both the water level (**stage**) and the velocity increase as well. Rapidly flowing streams become muddy and large volumes of sediment are transported both in suspension and along the stream bed. In extreme situations, the water level reaches the top of the stream's banks (the **bank-full stage**, see Figure 12.5.4), and if it rises any more, it floods the surrounding terrain. In the case of mature or old-age streams, this could include a vast area of relatively flat ground known as a flood plain, which is the area that is typically covered with water during a major flood. Because fine river sediments are deposited on flood plains, they are ideally suited for agriculture, and thus are typically occupied by farms and residences, and in many cases, by towns or cities. Such infrastructure is highly vulnerable to damage from flooding, and the people that live and work there are at risk.

ADVANCED TOPIC: THE PROBABILITY APPROACH TO RIVER FLOODS

1. The important question that arises is: *what can be done about establishing the probability of very large floods*? This is extremely important, but it's fraught with difficulties. Here's how it's done, given a long record of discharge at some location along the river (Figure 12.5.12):

- Determine the largest momentary discharge in each year.
- Rank these in order of decreasing discharge (the highest being number one, the lowest being equal to the number of years of record).
- Compute the ***recurrence interval*** (also called the ***return period***), in years: the average number of years within which a given event (i.e., a flood of given magnitude) will be equaled or exceeded), by the formula $T = (n+1)/m$, where T is the recurrence interval, n is the number of years in the record, and m is the rank of the event (or, equivalently, the probability p of a given event being equaled or exceeded in any given year; that's called the ***exceedence probability***).
- Plot the results in a graph with recurrence interval and/or exceedence probability on the horizontal axis and the annual maximum discharge on the vertical axis.
- Fit a smooth curve through the points in some way.



Flood-frequency curve plotted on logarithmic probability paper, Tana River at Garissa. Keny. 1934-1970. The scale at the top is the probability that the discharge is equaled or exceeded in any given year. The bottom scale, recurrence interval, is the average number of years in which the annual peak equals or exceeds the discharge given on the ordinate.

Figure 12.5.12: An example of a flood-frequency curve. (From Leopold, 1994.)

2. The results are reliable for the mid-range of the graph, but they become very uncertain near the high-discharge end because of the small numbers of very large events. Fitting such a tail of a distribution is always tricky business, but it is important if one is to try to extrapolate to much longer times, which is one of the important goals of such an exercise. Various techniques have been in use for fitting such a curve. Several such distributions have been in use. The trouble with blind curve fitting is that one or two unrepresentative or outlying points at the high-discharge end can bias the curve significantly.

3. One valuable approach is to try to determine, from historical records, whether the greatest discharge in the period of record was exceeded in earlier times. If the greatest discharge in the period of record can be established to have been greater than any other for a number of years before the period of record, the period of record can be extended back in time and the ranking redone. This tends to shift the unrepresentatively large outlying point to the right and bring it more closely in line with the rest of the distribution.

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12.6: Mineral Resources

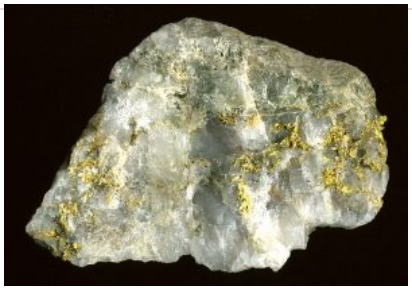


Figure 12.6.1: Gold-bearing quartz vein from California.

Mineral resources, while principally nonrenewable, are generally placed in two main categories: **metallic** (containing metals) or **nonmetallic** (containing other useful materials). Metallic minerals are those from which valuable metals (e.g. iron, copper) can be extracted for commercial use. Metals that are considered geochemically abundant occur at crustal abundances of 0.1 percent or more (e.g. iron, aluminum, manganese, magnesium, titanium). Metals that are considered geochemically scarce occur at crustal abundances of less than 0.1 percent (e.g. nickel, copper, zinc, platinum metals). Some important metallic minerals are: hematite (a source of iron), bauxite (a source of aluminum), sphalerite (a source of zinc) and galena (a source of lead). Metallic minerals occasionally but rarely occur as a single element (e.g. native gold or copper). Most mining is focused on metallic minerals. A significant part of the advancement of human society has been developing the knowledge and technologies that yielded metal from the Earth and allowed the machines, buildings, and monetary systems that dominate our world today. The location and recovery of these metals have been a key facet of the study of geology since its inception.



Minerals. SemiletovaOlga, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

While receiving much less attention, nonmetallic mineral resources (also known as industrial minerals) are just as vital to ancient and modern society as metallic minerals. Nonmetallic minerals are valuable, not for the metals they contain, but for their properties as chemical compounds. Because they are commonly used in industry, they are also often referred to as industrial minerals. They are classified according to their use. The most basic of these is building stone. Limestone, travertine, granite, slate, and marble are common building stones and have been quarried for centuries (Figure 12.6.2). Some industrial minerals are also used for building materials (e.g. gypsum for plaster and kaolin for bricks). Some industrial minerals are used as sources of important chemicals (e.g. halite for sodium chloride and borax for borates). For everything made out of concrete or asphalt, we need sand and gravel. To make the cement that holds concrete together, we also need limestone. Others are used for making fertilizers (e.g. apatite for

phosphate and sylvite for potassium). Still others are used as abrasives (e.g. diamond and corrundum). For the glass in our computer screens and for glass-sided buildings, we need silica sand plus sodium oxide (Na_2O), sodium carbonate (Na_2CO_3), and calcium oxide (CaO). For a wide range of applications (e.g., ceramics and many industrial processes), we also need various types of clay. Some nonmetallic mineral resources are not mineral specific; nearly any rock or mineral can be used. This is generally called aggregate and is used in concrete, roads, and foundations. Gravel is one of the more common aggregates. Quarried rock is also used in some applications where rounded gravel isn't suitable, such as the ballast (road bed) for railways, where crushed angular rock is needed.



Figure 12.6.2: Carrara marble quarry in Italy, source to famous sculptures like Michelangelo's David.

Mineral Deposits

Minerals are everywhere around us. For example, the ocean is estimated to contain more than 70 million tons of gold. Yet, it would be much too expensive to recover that gold because of its very low concentration in the water. Minerals must be concentrated into deposits to make their collection economically feasible. A mineral deposit containing one or more minerals that can be extracted profitably is called an **ore**. Many minerals are commonly found together (e.g. quartz and gold; molybdenum, tin and tungsten; copper, lead and zinc; platinum and palladium).

If the material can be mined at a profit, the body constitutes an **ore** deposit. Typically, the term ore is used for only metal-bearing minerals, though the concept of ore as a non-renewable resource can be applied to valuable concentrations of fossil fuels, building stones, and other non-metal deposits, even groundwater. Mineral **ores** are found in just a relatively few areas, because it takes a special set of circumstances to create them. Therefore, the signs of a mineral deposit are often small and difficult to recognize. Locating deposits requires experience and knowledge. Geologists can search for years before finding an economic mineral deposit. Deposit size, its mineral content, extracting efficiency, processing costs and market value of the processed minerals are all factors that determine if a mineral deposit can be profitably developed. For example, when the market price of copper increased significantly in the 1970s, some marginal or low-grade copper deposits suddenly became profitable ore bodies.

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12.7: Mining

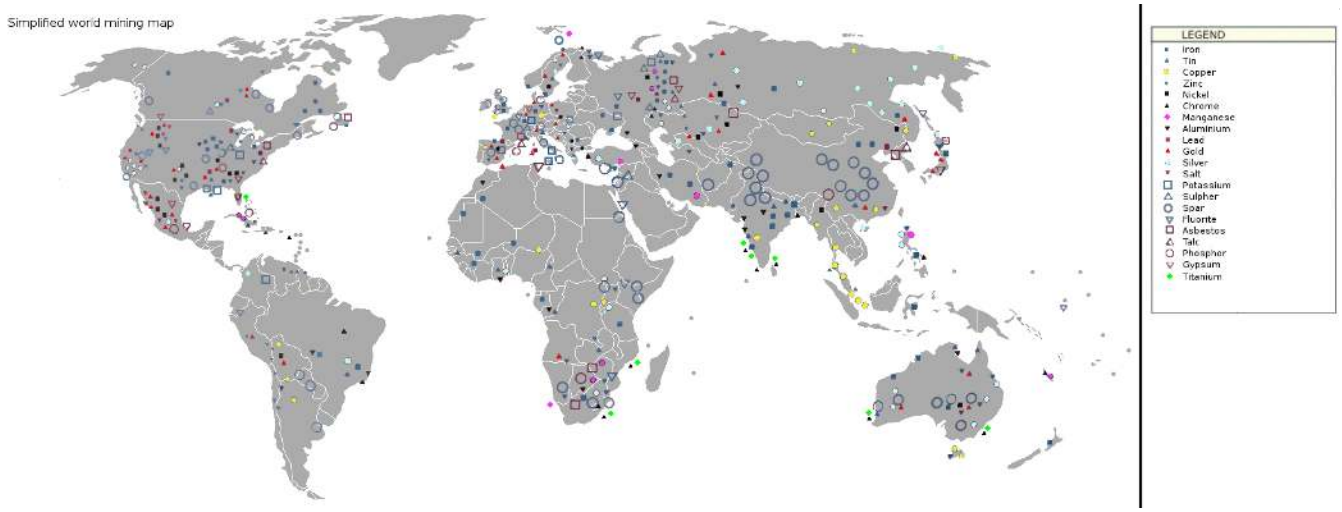


Figure 12.7.1: Map of world mining areas.

Mining is defined as the extraction, from the Earth, of valuable material for societal use. Usually, this includes solid materials (e.g. gold, iron, coal, diamond, sand, and gravel), but can also include fluid resources such as oil and natural gas. Modern mining has a long relationship with modern society. The oldest evidence of mining, with a concentrated area of digging into the Earth for materials, has a history that may go back 40,000 years to the hematite (used as red dye) of the Lion Cave in Swaziland [4]. Resources extracted by mining are generally considered to be nonrenewable. After a potentially profitable mineral deposit is located, it is mined by one of several techniques. Which technique is used depends upon the type of deposit and whether the deposit is shallow and thus suitable for surface mining or deep and thus requiring sub-surface mining. The style of mining is a function of technology, social license, and economics. It is in the best interest of the company extracting the resources to do so in a cost-effective way.

It is implicit that the technology to mine is available, economic conditions are suitable, and political, social and environmental considerations are satisfied in order to classify a natural resource deposit as ore. Depending on the substance, it can be concentrated in a narrow vein or distributed over a large area as a low-concentration ore. Some materials are mined directly from bodies of water (e.g. sylvite for potassium; water through desalination) and the atmosphere (e.g. nitrogen for fertilizers). These differences lead to various methods of mining, and differences in terminology depending on the certainty. **Ore mineral resource** is used for an indication of ore that is potentially extractable, and the term **ore mineral reserve** is used for a well defined (proven), profitable amount of extractable ore.

Surface Mining Techniques

Surface mining techniques include: open-pit mining, area strip mining, contour strip mining and hydraulic mining. **Open-pit mining** involves digging a large, terraced hole in the ground in order to remove a near-surface ore body (Figure 12.7.2). This technique is used in copper ore mines in Arizona and Utah and iron ore mines in Minnesota. Typically, the pit progressively deepens through additional mining cuts to extract the ore, and the walls of the pit are as steep as can safely be managed. A steep wall means there is less waste (non-valuable) rock or overburden to remove and is an engineering balance between efficient mining and mass wasting. Occasionally landslides do occur, including a very large landslide that occurred in the Bingham Canyon mine in 2013. These events are costly and dangerous, though careful monitoring gave the Bingham Canyon mine ample warning time.



Figure 12.7.2: **Open Pit Mine** Bingham Canyon copper mine in Utah, USA. At 4 km wide and 1.2 km deep, it is the world's deepest open-pit mine. It began operations in 1906. *Source: Tim Jarrett via Wikimedia Commons*

Area strip mining is used in relatively flat areas. The overburden of soil and rock is removed from a large trench in order to expose the ore body. After the minerals are removed, the old trench is filled and a new trench is dug. This process is repeated until the available ore is exhausted. **Contour strip mining** is a similar technique except that it is used on hilly or mountainous terrains. A series of terraces are cut into the side of a slope, with the overburden from each new terrace being dumped into the old one below. In **mountaintop removal mining**, a specific type of strip mining, an entire mountaintop or rock layer is removed to gain access to the ore below. The environmental impacts of surface mining are usually greater due to the larger surface disturbance footprint [7].



Figure 12.7.3: A surface coal mine in Wyoming.

Hydraulic mining is used in places such as the Amazon in order to extract gold from hillsides. Powerful, high-pressure streams of water are used to blast away soil and rock containing gold, which is then separated from the runoff. This process is very damaging to the environment, as entire hills are eroded away and streams become clogged with sediment. If land subjected to any of these surface mining techniques is not properly restored after its use, then it leaves an unsightly scar on the land and is highly susceptible to erosion.

Sub-Surface Mining Techniques

Some mineral deposits are too deep to be surface mined and therefore require a **sub-surface mining** method. **Underground mining** is often used for higher-grade, more localized, or very concentrated resources. In the traditional sub surface method a deep vertical shaft is dug and tunnels are dug horizontally outward from the shaft into the ore body. The ore is removed and transported

to the surface. The deepest such subsurface mines (deeper than 3500 m) in the world are located in the Witwatersrand basin of South Africa, where gold is mined. This type of mining is less disturbing to the land surface than surface mining. It also usually produces fewer waste materials. However, it is more expensive and more dangerous than surface mining methods.

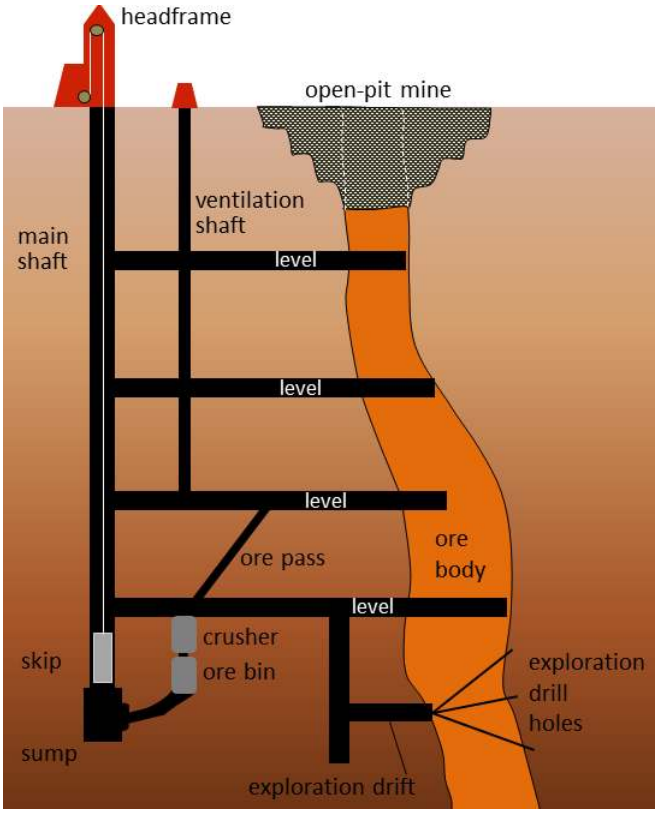


Figure 12.7.4: *Schematic cross-section of a typical underground mine.* © Steven Earle. CC BY



Figure 12.7.5: Underground mining in Estonia of Oil Shale.

A newer form of subsurface mining known as **in-situ mining** is designed to co-exist with other land uses, such as agriculture. An in-situ mine typically consists of a series of injection wells and recovery wells built with acid-resistant concrete and polyvinyl chloride casing. A weak acid solution is pumped into the ore body in order to dissolve the minerals. Then, the metal-rich solution is drawn up through the recovery wells for processing at a surface refining facility where the mineral of interest is precipitated. This method is used for the in-situ mining of copper ore.

Ore Processing

Once an ore has been mined, it must be processed to extract pure metal. All ore minerals are mixed with less desirable components called **gangue**. The process of physically separating gangue minerals from ore-bearing minerals is called **concentrating**. When ore

is processed (typically very close to the mine), it is ground to a fine powder and the ore minerals are physically separated from the rest of the rock to make a **concentrate**. At a molybdenum mine, for example, this concentrate may be almost pure molybdenite (MoS_2). The rest of the rock is known as **tailings**. It comes out of the concentrator as a wet slurry and must be stored near the mine, in most cases, in a tailings pond. The tailings pond at the Myra Falls Mine on Vancouver Island is shown in Figure 12.7.6, and the settling ponds for waste water from the concentrator are shown in Figure 12.7.7. The tailings are contained by an embankment. Also visible in the foreground of Figure 12.7.6 is a pile of waste rock, which is non-ore rock that was mined in order to access the ore. Although this waste rock contains little or no ore minerals, at many mines it contains up to a few percent pyrite.

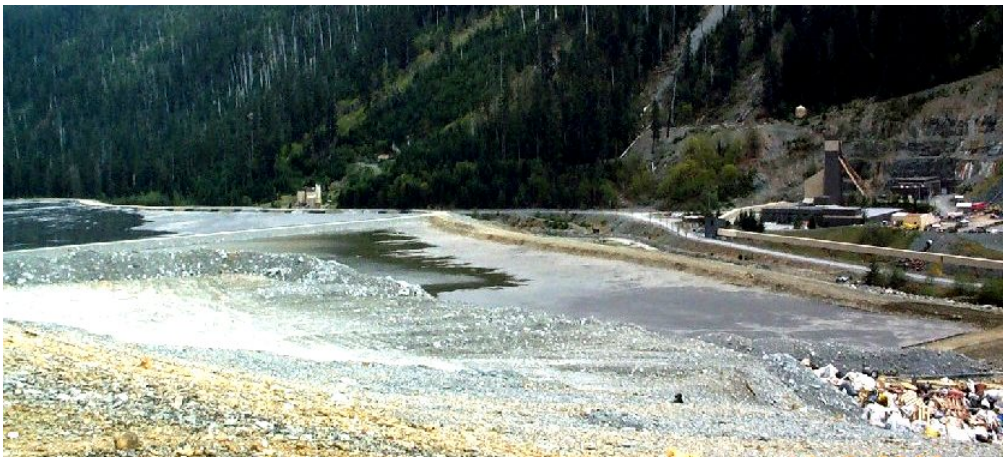


Figure 12.7.6: *The tailings pond at the Myra Falls Mine on Vancouver Island. The dry rock in the middle of the image is waste rock. The structure on the right is the headframe for the mine shaft. Myra Creek flows between the tailings pond and the headframe.* © Steven Earle. CC BY

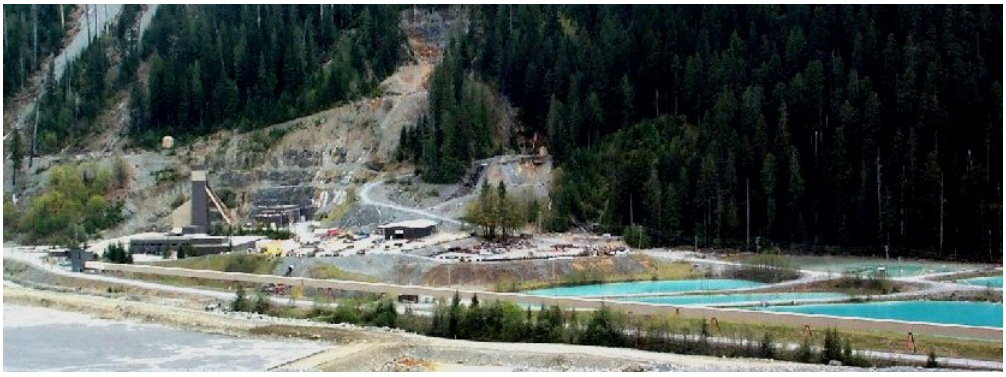


Figure 12.7.7: *The tailings pond (lower left) at Myra Falls Mine with settling ponds (right) for processing water from the concentrator.* © Steven Earle. CC BY

Processes for extracting metal include smelting, electrowinning and heap leaching. In preparation for the **smelting** process, the ore is crushed and concentrated by a flotation method. The concentrated ore is melted in a smelting furnace where impurities are either burned-off as gas or separated as molten slag (Figure 12.7.8). **Slag** is the glassy unwanted by-product of smelting ore and is sometimes mistaken for metorites. The smelting step is usually repeated several times to increase the purity of the metal.

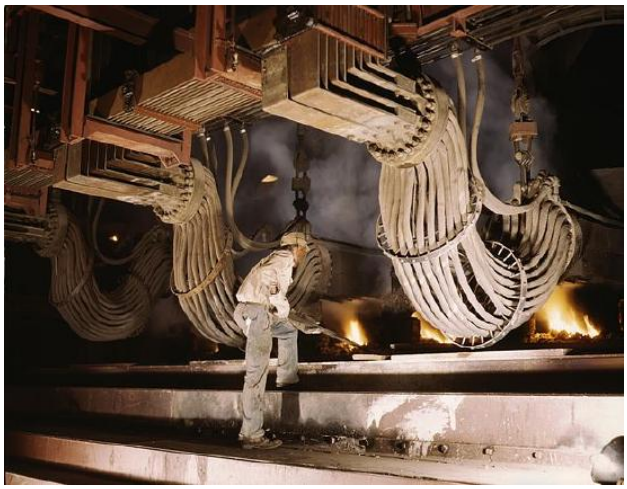


Figure 12.7.8: A phosphate smelting operation in Alabama, 1942.

For the **electrowinning** method ore or mine tailings are first leached with a weak acid solution to remove the desired metal. An electric current is passed through the solution and pure metal is electroplated onto a starter cathode made of the same metal. Copper can be refined from oxide ore by this method. In addition, copper metal initially produced by the smelting method can be purified further by using a similar electrolytic procedure.

Gold is sometimes extracted from ore by the **heap leaching** process. A large pile of crushed ore is sprayed with a cyanide solution. As the solution percolates through the ore it dissolves the gold. The solution is then collected and the gold extracted from it. All of the refining methods can damage the environment. Smelters produce large amounts of air pollution in the form of sulfur dioxide which leads to acid rain. Leaching methods can pollute streams with toxic chemicals that kill wildlife.

Environmental Impacts of Metallic Mineral Mining

The primary impact of metallic mineral mining comes from the mining itself, including disturbance of the land surface, covering of landscapes by tailings impoundments, and increased mass wasting by accelerated erosion [48]. Surface mines can create enormous pits (Figure 12.7.2) in the ground as well as large piles of overburden and tailings that need to be **reclaimed**, i.e., restored to a useful landscape. Since 1977 surface mines in U.S. are required to be reclaimed, and commonly reclamation is relatively well done in this country. Unfortunately, surface mine reclamation is not done everywhere, especially in underdeveloped countries, due to lack of regulations or lax enforcement of regulations. Unreclaimed surface mines and active surface mines can be major sources of water and sediment pollution.

In addition, many metal deposits contain pyrite, an uneconomic sulfide mineral placed on waste dumps, which may generate **acid rock drainage** (ARD) during weathering (Figure 12.7.9). In the presence of oxygenated water, sulfides such as pyrite react undergo complex reactions to release metal ions and hydrogen ions, lowering pH to highly acidic levels. Mining and processing of mined materials typically increase the surface area to volume ratio in the material, causing reactions to occur even faster than what would occur naturally. If not managed properly, these reactions may lead to acidification of streams and groundwater plumes that can carry dissolved toxic metals. In mines where limestone is a waste rock of carbonate minerals like calcite or dolomite are present, their acid-neutralizing potential helps reduce the likelihood of generating ARD. Although this is a natural process too, it is very important to isolate mine dumps and tailings from oxygenated water, both to prevent the dissolution of sulfides and subsequent percolation of the sulfate-rich water into waterways. Industry has taken great strides in preventing contamination in recent decades, but earlier mining projects are still causing problems with local ecosystems.



Figure 12.7.9: **Acid Mine Drainage** The water in Rio Tinto River, Spain is highly acidic (pH = ~2) and the orange color is from iron in the water. A location along this river has been mined beginning some 5,000 years ago primarily for copper and more recently for silver and gold. *Source: Sean Mack of NASA via Wikimedia Commons*

Tailings ponds and waste-rock storage piles must be carefully maintained to ensure their integrity and monitored to ensure that acidic and metal-rich water is not leaking out. In August 2014, the tailings pond at the Mt. Polley Mine in central B.C. failed and 10 million cubic metres of waste water along with 4.5 million cubic metres of tailings slurry was released into Polley Lake, Hazeltine Creek, and Quesnel Lake (Figure 12.7.10 – 11). As of July 2015, the environmental implications of this event are still not fully understood.

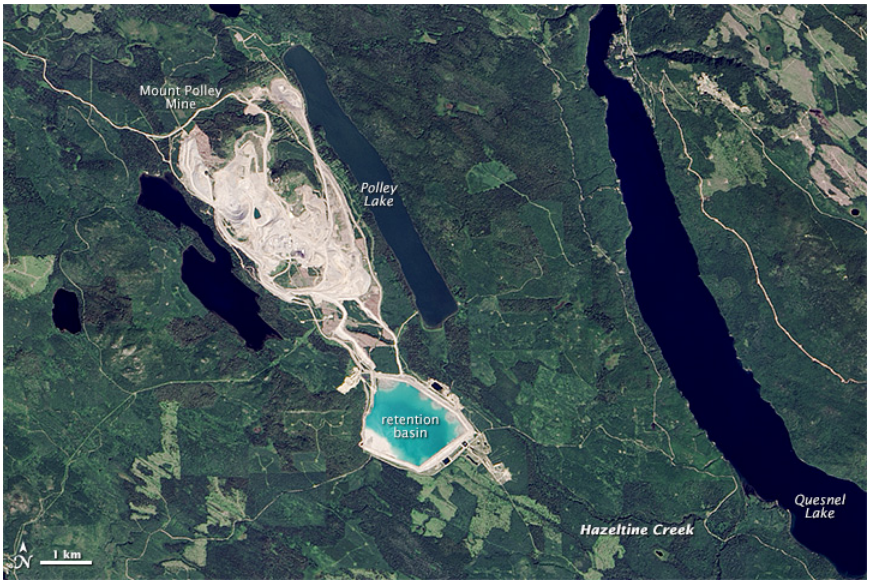


Figure 12.7.10: *The Mt. Polley Mine area prior to the dam breach of August 2014. The tailings were stored in the area labelled "retention basin." [https://en.Wikipedia.org/wiki/Mount_...mine_disaster]*



Figure 12.7.11: *The Mt. Polley Mine area after the tailings dam breach of August 2014. The water and tailings released flowed into Hazeltine Creek, and Polley and Quesnel Lakes. [https://en.Wikipedia.org/wiki/Mount_...mine_disaster]*

MINERAL SUFFICIENCY AND THE FUTURE

Mineral resources are essential to life as we know it. A nation cannot be prosperous without a reliable source of minerals, and no country has all the mineral resources it requires. The United States has about 5 percent of the world's population and 7 percent of the world's land area, but uses about 30 percent of the world's mineral resources. It imports a large percentage of its minerals; in some cases sufficient quantities are unavailable in the U.S., and in others they are cheaper to buy from other countries. Certain minerals, particularly those that are primarily imported and considered of vital importance, are stockpiled by the United States in order to protect against embargoes or other political crises. These strategic minerals include: bauxite, chromium, cobalt, manganese and platinum.

Because minerals are produced slowly over geologic time scales, they are considered non-renewable resources. The estimated mineral deposits that are economically feasible to mine are known as mineral reserves. The growing use of mineral resources throughout the world raises the question of how long these reserves will last. Most minerals are in sufficient supply to last for many years, but a few (e.g. gold, silver, lead, tungsten and zinc) are expected to fall short of demand in the near future. Currently, reserves for a particular mineral usually increase as the price for that mineral increases. This is because the higher price makes it economically feasible to mine some previously unprofitable deposits, which then shifts these deposits to the reserves. However, in the long term this will not be the case because mineral deposits are ultimately finite.

There are ways to help prolong the life of known mineral reserves. Conservation is an obvious method for stretching reserves. If you use less, you need less. Recycling helps increase the amount of time a mineral or metal remains in use, which decreases the demand for new production. It also saves considerable energy, because manufacturing products from recycled metals (e.g. aluminum, copper) uses less energy than manufacturing them from raw materials. Government legislation that encourages conservation and recycling is also helpful. The current "General Mining Act of 1872," however, does just the opposite. It allows mining companies to purchase government land very inexpensively and not pay any royalties for minerals extracted from that land. As a result, mineral prices are kept artificially low which discourages conservation and recycling.

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12.8: Fossil Fuels- Formation and Mining

Fossil fuels are nonrenewable sources of energy formed from the organic matter of plants and microorganisms that lived millions of years ago. The natural resources that typically fall under this category are coal, oil (petroleum), and natural gas. This energy (and CO_2) 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. Of course, as the energy is used, just like respiration from photosynthesis that occurs today, carbon can enter the atmosphere, causing climate consequences. 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.

The conversion of living organisms into fossil fuels is a complex process. As organisms die, most organic matter is oxidized back to CO_2 relatively quickly (within weeks or years in most cases), but any of it that gets isolated from the oxygen of the atmosphere (for example, deep in the ocean or in a stagnant bog) may last long enough to be buried by sediments and, if so, may be preserved for tens to hundreds of millions of years and the chemical energy within the organisms' tissues is added to surrounding geologic materials. Higher productivity in the ancient environment leads to a higher potential for fossil fuel accumulation, and there is some evidence of higher global biomass and productivity over geologic time [8]. Lack of oxygen and moderate temperatures seem to enhance the preservation of these organic substances [9; 10]. Heat and pressure that is applied after burial also can cause transformation into higher quality materials (brown coal to anthracite, oil to gas) and/or migration of mobile materials [11].

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, the first fossil fuel to be widely used, forms mostly on land in swampy areas adjacent to rivers and deltas in areas with humid tropical to temperate climates. 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 12.8.1). 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). This situation, where the dead organic matter is submerged in oxygen-poor water, must be maintained for centuries to millennia in order for enough material to accumulate to form a thick layer. At some point, the peat was buried — typically because a river changes its course or sea level rises — and formed coal after millions of years of high pressure and temperature.

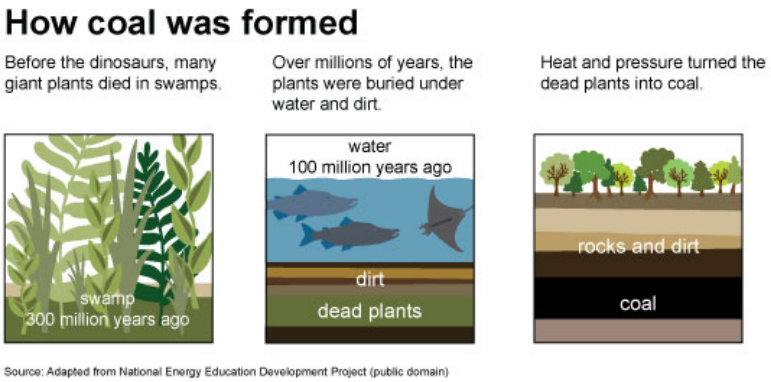


Figure 12.8.1**:** Coal was formed when large plants in swamps died 300 million years ago (before the dinosaurs). Over millions of years, this vegetation was buried under water and dirt (100 million years ago). Eventually, heat and pressure turned the dead plants into coal, which is found under layers 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 12.8.2). 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

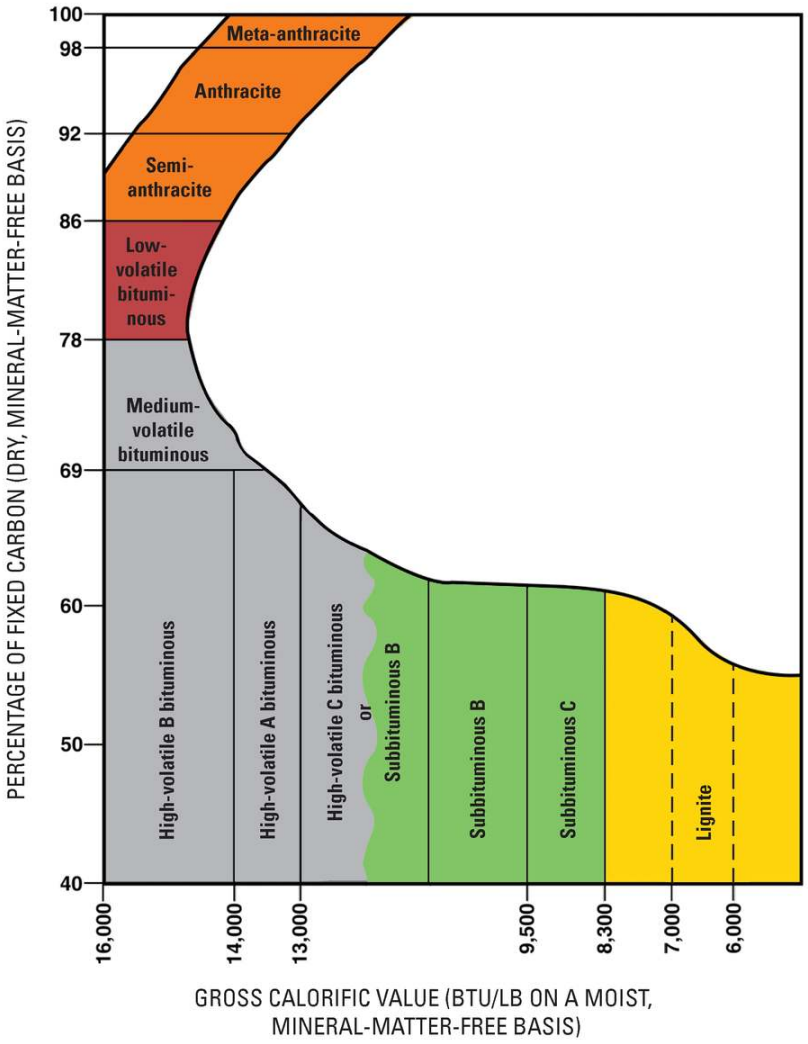


Figure 12.8.2**:** Coal rankings depend on energy content, measured as gross calorific value (how much energy is released from combustion) and carbon content that can be burned (percentage of fixed carbon). Anthracitic coal (orange) is the highest quality coal, with high energy and carbon content. Next 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 subbitminous 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 12.8.3). 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 12.8.3**:** Anthracitic coal, the highest grade of coal.

Mining Coal

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 12.8.4). **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.



Figure 12.8.4**:** Surface mining of coal in Wyoming. Image by Bureau of Land Management (public domain).

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 12.8.5). The large mass of overburden (the mountaintop) is dumped into a nearby valley, and the coal is them removed.



Figure 12.8.5**:** 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 12.8.6). 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.

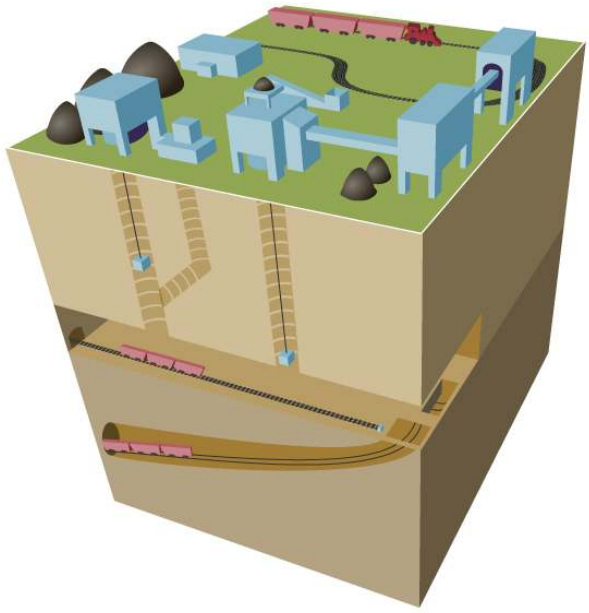


Figure 12.8.6**:** Subsurface mining involves digging tunnels to access coal deposits that are deep underground. Image by National Energy Education Development Project/EIA (public domain)

There are also significant health effects and risks to coal miners and those living in the vicinity of coal mines. Traditional underground mining is risky to mine workers due to the risk of entrapment or death. Over the last 15 years, the U.S. Mine Safety and Health Administration has published the number of mine worker fatalities and it has varied from 18-48 per year. Twenty-nine miners died on April 6, 2010 in an explosion at the Upper Big Branch coal mine in West Virginia, contributing to the uptick in

deaths between 2009 and 2010. In other countries, with less safety regulations, accidents occur more frequently. In May 2011, for example, three people died and 11 were trapped in a coalmine in Mexico for several days. There is also risk of getting **black lung disease** (pneumoconiosis). This is a disease of the lungs caused by the inhalation of coal dust over a long period of time**.** It causes coughing and shortness of breath. If exposure is stopped the outcome is good. However, the complicated form may cause shortness of breath that gets increasingly worse. **Mountaintop mining** (MTM), while less hazardous to workers, has particularly detrimental effects on land resources. MTM is a surface mining practice involving the removal of mountaintops to expose coal seams, and disposing of the associated mining waste in adjacent valleys. This form of mining is very damaging to the environment because it literally removes the tops of mountains, destroying the existing habitat. Additionally, the debris from MTM is dumped into valleys burying streams and other important habitat.



Figure 12.8.7**:** Mountaintop Removal Coal Mining in Martin County, Kentucky Photograph shows mountaintop coal removal mining in Martin County, Kentucky. Source: Flashdark.

Oil and Gas

Petroleum, with the liquid component commonly called **oil** and gas component called **natural gas** (mostly made up of methane), is principally derived from organic-rich shallow marine sedimentary deposits [12] formed from ancient marine microorganisms (**plankton**) (Figure 12.8.8). 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. As the depth of burial increases, so does the temperature—due to the geothermal gradient—and gradually the organic matter within the sediments is converted to hydrocarbons. The first stage is the biological production (involving anaerobic bacteria) of methane. Most of this escapes back to the surface, but some is trapped in methane hydrates near the sea floor. At depths beyond about 2 km, and at temperatures ranging from 60° to 120°C, the organic matter is converted by chemical processes to oil. This depth and temperature range is known as the **oil window**. Beyond 120°C most of the organic matter is chemically converted to methane. (Some natural gas is also found associated with coal deposits (**coalbed methane**), consisting of methane produced during coal formation.)

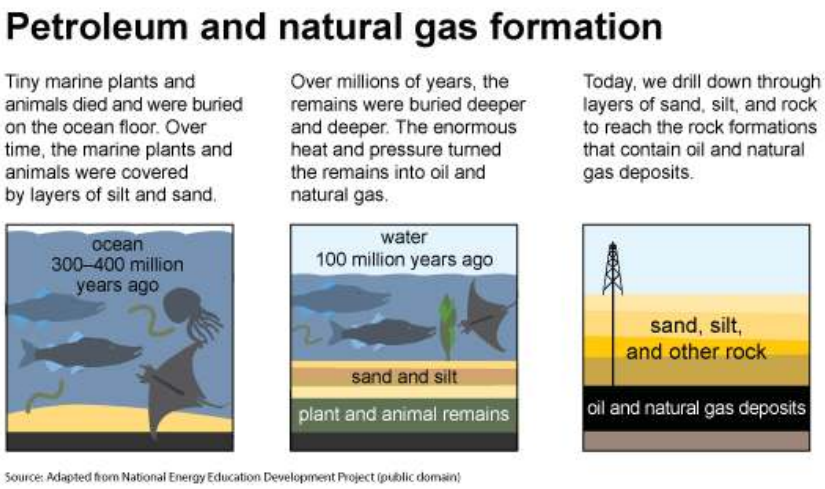


Figure 12.8.8**:** Petroleum (oil) and natural gas were formed from marine microorganisms. (The image text mentions tiny marine plants, but they were primarily algae and photosynthetic bacteria rather than plants.) These were covered by layers of silt and sand 300-400 million years ago. Over millions 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 12.8.9). 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.

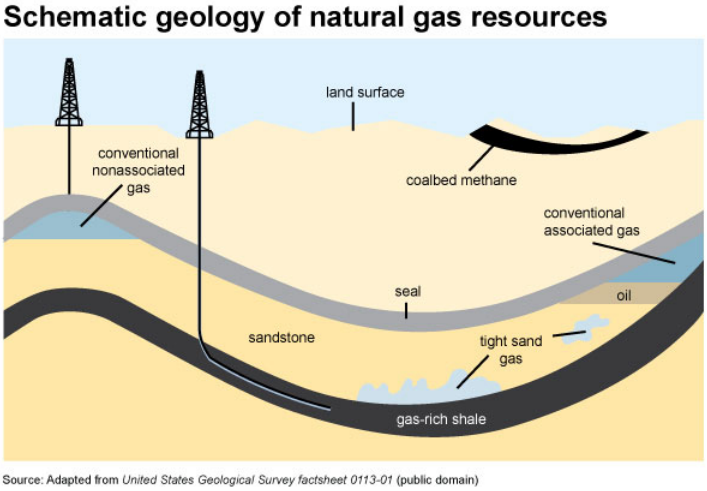


Figure 12.8.9**:** Conventional oil and natural gas deposits are trapped beneath impervious rock (gray). Conventional natural gas may be associated with oil or nonassociated. Coalbed methane and tight gas found in shale and sandstone are examples of unconventional fossil fuels. Image from USGS/EIA (public domain)

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 12.8.10). Each stage of recovery is increasingly expensive, and extraction from a well continues as long as it remains profitable.



Figure 12.8.10**:** 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 12.8.11). 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 12.8.11**:** 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 (fine-grained sedimentary rocks with relatively high porosity and low permeability) as well as natural gas in tight sands (gas-bearing, fine-grained sandstones or carbonates with a low permeability) 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 12.8.12).

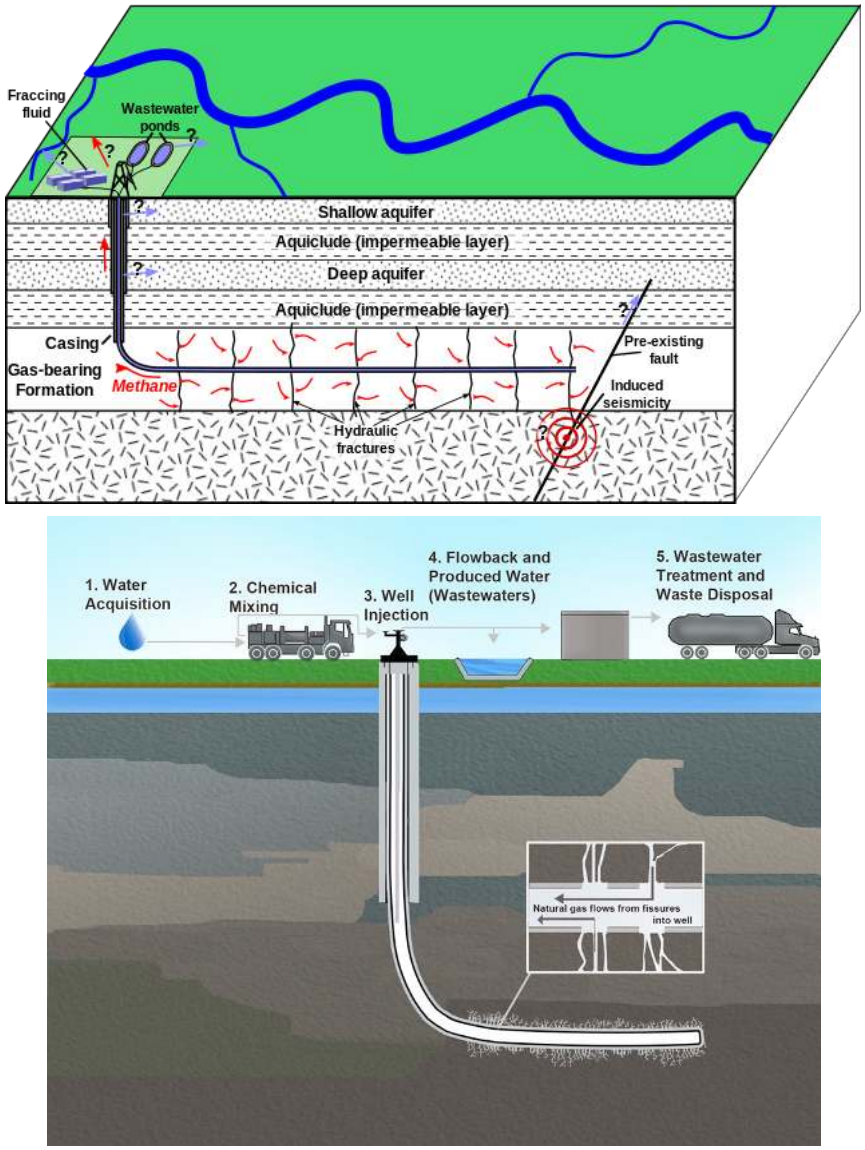


Figure 12.8.12**:** Two diagrams of fracking. Water is mixed with sand and chemicals and then injected into shale trapping tight oil and natural gas or tight sand. This flushes fossil fuels from the fissures that were previously created by explosives. Top: This section shows four underground layers. 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).

Fracking causes more environmental damage than conventional extraction. The considerable use of water (figure 12.8.13) 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 12.8.13). 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.

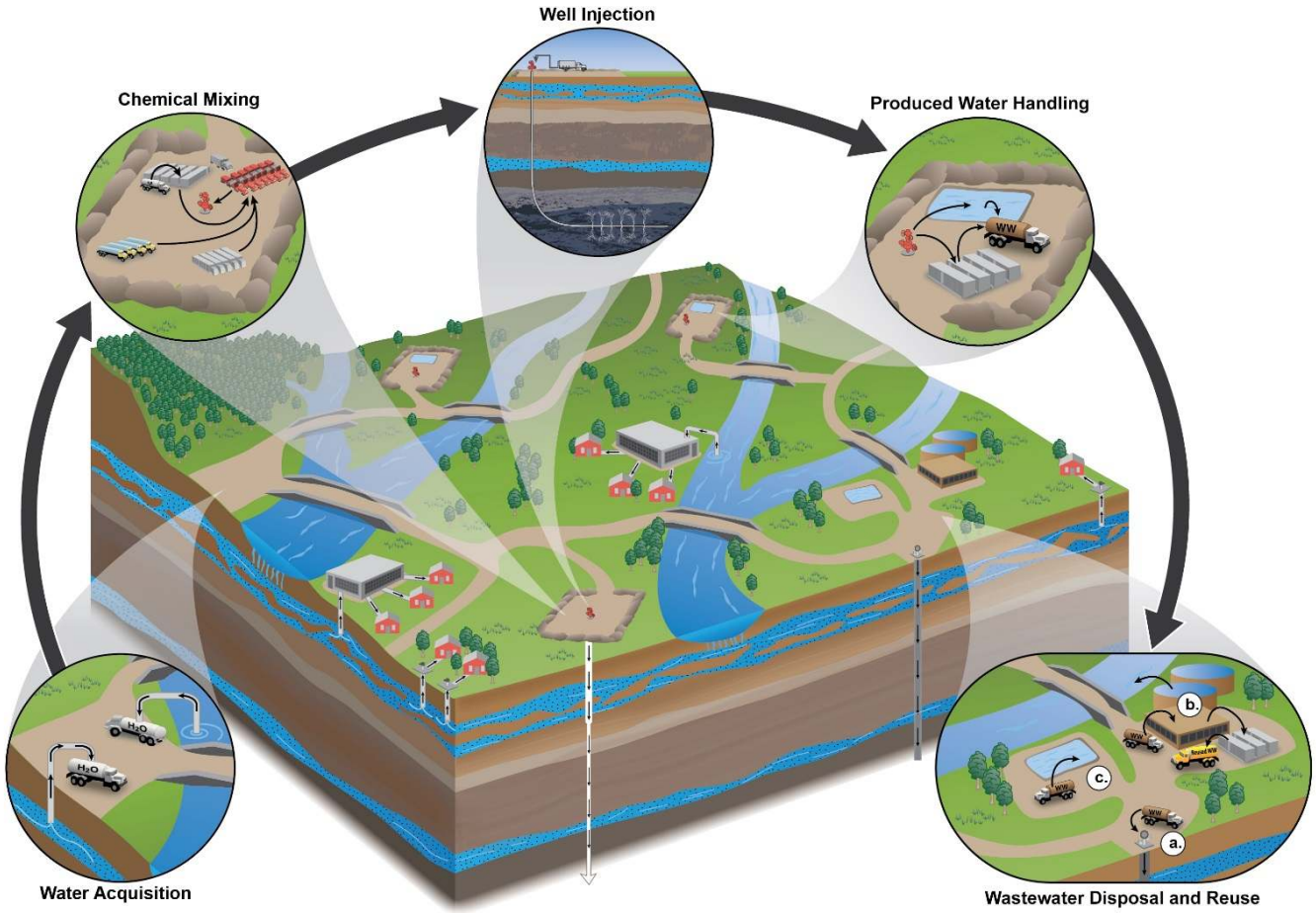


Figure 12.8.13**:** Fracking influences the water cycle. Water acquisition is the withdrawal of groundwater or surface water to make hydraulic fracturing fluids. Chemical mixing involves combining a base fluid, sand, and additives at the well site to create hydraulic fracturing fluids. During well injection, 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).

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 12.8.14). They are “unconventional” because the oil is exposed near the surface and is highly viscous because of microbial changes that have taken place at the surface. 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. 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. Alberta, Canada is known to have the largest reserves of tar sands in the world.



Figure 12.8.14**:** Tar sandstone from the Miocene Monterrey Formation of California.

The oil sands are controversial primarily because of the environmental cost of their extraction. Since the oil is so viscous, it requires heat to make it sufficiently liquid to process. This energy comes from gas; approximately 25 m^3 of gas is used to produce 0.16 m^3 (one barrel) of oil. (That's not quite as bad as it sounds, as the energy equivalent of the required gas is about 20% of the energy embodied in the produced oil.)

Oil shale (or tight oil) is a fine-grained sedimentary rock that sometimes contains **kerogen**, a solid material from which petroleum products can ultimately be manufactured. Shale is a common source of fossil fuels with high porosity but it has very low permeability. 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. 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 12.8.15). In order to get the oil out, the material has to be mined and heated, which, like with tar sands, is expensive and typically has a negative impact on the environment [17].



Figure 12.8.15: Underground mining of oil shale in Estonia.

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CHAPTER OVERVIEW

13: Energy

13.1: What is Energy?
13.2: Challenges and Impacts of Energy Use
13.3: Non-Renewable Energy Sources
13.4: Coal
13.5: Oil
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13.13: Biofuels (Biomass Energy)
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13.1: What is Energy?

Learning Objectives

By the end of this chapter, students will be able to

- List specific examples of non-renewable energy sources
- Explain what makes an energy source non-renewable
- Describe the main types of fossil fuels and how they formed
- Explain the environmental impacts associated with exploration, extraction and use of the different types of fossil fuels
- Explain nuclear energy, how it works, its benefits and risks



Watts Bar Nuclear Power Plant in East Tennessee. Image from Tennessee Valley Authority (Public Domain).

Energy is the ability of a system to do work. A system has done work if it has exerted a force on another system over some distance. When this happens, energy is transferred from one system to another. At least some of the energy is also transformed from one type to another during this process. One can keep track of how much energy transfers into or out of a system. There are two categories that all energy falls into: kinetic and potential. **Kinetic energy** refers to types of energy associated with motion (Figure 13.1.1, top). For example, a rock rolling down a hill, the wind blowing through trees, water flowing over a dam, and a cyclist riding a bicycle are just a few examples of kinetic energy. **Potential energy** is energy possessed by an object or system due to its position in space relative to another object or system and forces between the two (Figure 13.1.1, bottom). Examples include a rock poised at the top of a hill and water stored behind a dam. Some forms of energy are part kinetic and part potential energy. **Chemical energy** describes the potential of a chemical substance to undergo a chemical reaction and transform other chemical substances; hence it is a form of potential energy. Examples include energy stored in the food you eat and the gasoline that you put in your car.



Figure 13.1.1**:** *Examples kinetic (top) and potential (bottom) forms of energy. All images were obtained from Wikimedia commons (public domain).*

Living organisms need energy to perform life-sustaining “work” in order to survive. For nearly all living systems on Earth, the sun is the ultimate source of that energy. Over time, we humans have developed an understanding of energy that has allowed us to harness it for uses well beyond basic survival. The development and evolution of human society is largely attributed to our relationship with energy. The first major advancement in human understanding of energy was the mastery of fire for cooking and heating. Modern civilization is especially dependent on energy and some of its most distinct characteristics such as population growth, environmental impact and climate change are all a consequence of energy use. We use energy to heat and light our homes; power our machinery; fuel our vehicles; produce plastics, pharmaceuticals, and synthetic fibers; and provide the comforts and conveniences to which we have grown accustomed in the industrial age. Societal complexity, affluence, and the gap between poor and rich peoples are all related to our level of energy consumption.

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13.2: Challenges and Impacts of Energy Use

Energy for lighting, heating and cooling our buildings, manufacturing products, and powering our transportation systems comes from a variety of natural sources. The earth's core provides geothermal energy. The gravitational pull of moon and sun create tides. The sun emits light (electromagnetic radiation), which creates wind, powers the water (hydrologic) cycle, and enables photosynthesis. Plants, algae, and cyanobacteria utilize solar energy to grow and create biomass that can be burned and used for **biofuels**, such as wood, biodiesel, bioethanol. Over the course of millions of years, biomass from photosynthetic organisms can create energy-rich **fossil fuels** through the geologic process of burial and transformation through heat and pressure.

Each of these types of energy can be defined as **renewable** or **non-renewable.** Renewable energy sources can be replenished within human lifespans. Examples include solar, wind, and biomass energy. Non-renewable energy is finite and cannot be replenished within a human timescale. Examples include nuclear energy and fossil fuels, which take millions of years to form. All energy sources have and some environmental and health cost, and the distribution of energy is not equally distributed among all nations.

Environmental and Health Challenges of Energy Use

The environmental impacts of energy use on humans and the planet can happen anywhere during the life cycle of the energy source. The impacts begin with the extraction of the resource. They continue with the processing, purification or manufacture of the source; its transportation to place of energy generation, and ends with the disposal of waste generated during use.

Extraction of fossil fuels can be used as a case study because its use has significant impacts on the environment. As we mine deeper into mountains, farther out at sea, or farther into pristine habitats, we risk damaging fragile environments, and the results of accidents or natural disasters during extraction processes can be devastating. 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. When transported by rail or truck energy must be expended and pollutants are generated. Processing of petroleum, gas and coal generates various types of emissions and wastes, as well as utilizes water resources. Production of energy at power plants results in air, water, and, often, waste emissions. Power plants are highly regulated in the Unites States by federal and state law under the Clean Air and Clean Water Acts, while nuclear power plants are regulated by the Nuclear Regulatory Commission.

Geopolitical Challenges of Fossil Fuels

The use of fossil fuels has allowed much of the global population to reach a higher standard of living. However, this dependence on fossil fuels results in many significant impacts on society. Our modern technologies and services, such as transportation and plastics depend in many ways on fossil fuels. If supplies become limited or extremely costly, our economies are vulnerable. If countries do not have fossil fuel reserves of their own, they incur even more risk. The United States has become more and more dependent on foreign oil since 1970 when our own oil production peaked. The United States imported over half of the crude oil and refined petroleum products that we consumed during 2009. Just over half of these imports came from the Western Hemisphere (Figure 13.2.2).

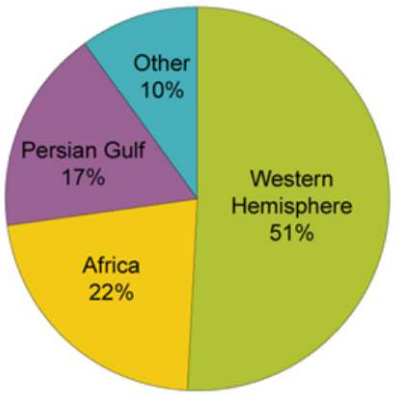


Figure illustrates that the United States imported over half of the crude oil and refined petroleum products that it consumed during 2009. Source: U.S. Energy Information Administration, Petroleum Supply Annual, 2009, preliminary data.

The major holder of oil reserves is the **Organization of Petroleum Exporting Countries,** (OPEC) (Figure 13.2.3). As of 2018, there were 15 member countries in OPEC: Algeria, Angola, Congo, Ecuador, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela. OPEC attempts to influence the amount of oil available to the world by assigning a production quota to each member except Iraq, for which no quota is presently set.

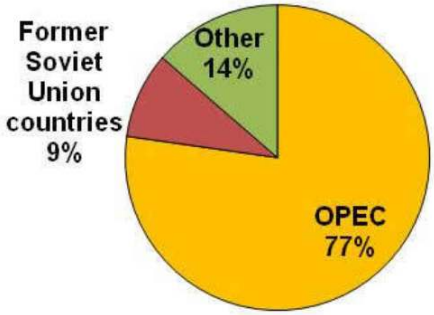


Figure 13.2.3. Proven Oil Reserves Holders Pie chart shows proven oil reserves holders. Source: C. Klein-Banai using data from BP Statistical Review of World Energy (2010)

Overall compliance with these quotas is mixed since the individual countries make the actual production decisions. All of these countries have a national oil company but also allow international oil companies to operate within their borders. They can restrict the amounts of production by those oil companies. Therefore, the OPEC countries have a large influence on how much of world demand is met by OPEC and non-OPEC supply. A recent example of this is the price increases that occurred during the year 2011 after multiple popular uprisings in Arab countries, including Libya.

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.

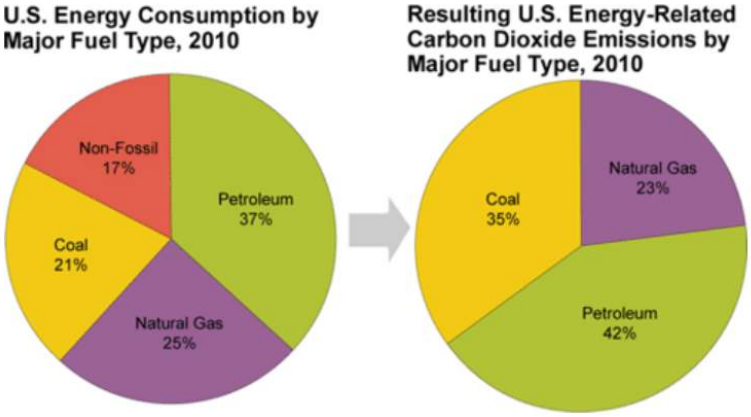


Figure 13.2.4. Fuel Type and Carbon Emissions The two charts show the relationship between fuel type and carbon emissions for U.S. energy consumption in 2010. Source: U.S. Energy Information Administration

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13.3: Non-Renewable Energy Sources

Fossil Fuels

Fossil fuels comes from the organic matter of plants, algae, and cyanobacteria that was buried, heated, and compressed under high pressure over millions of years. The process transformed the biomass of those organisms into the three types of fossil fuels: oil, coal, and natural gas.

Petroleum (oil)

Thirty seven percent of the world's energy consumption and 43% of the United States energy consumption comes from oil. Scientists and policy-makers often discuss the question of when the world will reach **peak oil production**, the point at which oil production is at its greatest and then declines. It is generally thought that peak oil will be reached by the middle of the 21st Century, although making such estimates is difficult because a lot of variables must be considered. Currently world reserves are 1.3 trillion barrels, or 45 years left at current level of production..

Environmental Impacts of Oil Extraction and Refining

Oil is usually found one to two miles (1.6 – 3.2 km) below the Earth's surface, whether that is on land or ocean. Once oil is found and extracted it must be refined, which separates and prepares the mix of crude oil into the different types for gas, diesel, tar, and asphalt. Oil refining is one of top sources of air pollution in the United States for volatile organic hydrocarbons and toxic emissions, and the single largest source of carcinogenic benzene. When petroleum is burned as gasoline or diesel, or to make electricity or to power boilers for heat, it produces a number of emissions that have a detrimental effect on the environment and human health:

- Carbon dioxide (CO_2) is a greenhouse gas and a source of climate change.
- Sulfur dioxide (SO_2) causes acid rain, which damages plants and animals that live in water, and it increases or causes respiratory illnesses and heart diseases, particularly in vulnerable populations like children and the elderly.
- Nitrous oxides (NO_x) and Volatile Organic Carbons (VOCs) contribute to ozone at ground level, which is an irritant and causes damage to the lungs.
- Particulate Matter (PM) produces hazy conditions in cities and scenic areas, and combines with ozone to contribute to asthma and chronic bronchitis, especially in children and the elderly. Very small, or "fine PM," is also thought to penetrate the respiratory system more deeply and cause emphysema and lung cancer.
- Lead can have severe health impacts, especially for children.

There are other domestic sources of oil that are being considered as conventional resources and are being depleted. These include **tar sands** – deposits of moist sand and clay with 1-2 percent bitumen (thick and heavy petroleum rich in carbon and poor in hydrogen). These are removed by strip mining (see section below on coal). Another source is **oil shale,** which is sedimentary rock filled with organic matter that can be processed to produce liquid petroleum. Extracted by strip mining or creating subsurface mines, oil shale can be burned directly like coal or baked in the presence of hydrogen to extract liquid petroleum. However, the net energy values are low and they are expensive to extract and process. Both of these resources have severe environmental impacts due to strip mining, carbon dioxide, methane and other air pollutants similar to other fossil fuels.

As the United States tries to extract more oil from its own dwindling resources, they are drilling even deeper into the earth and increasing the environmental risks. The largest United States oil spill to date began in April 2010 when an explosion occurred on Deepwater Horizon Oil Rig killing 11 employees and spilling nearly 200 million gallons of oil before the resulting leak could be stopped. Wildlife, ecosystems, and people's livelihood were adversely affected. A lot of money and huge amounts of energy were expended on immediate clean-up efforts. The long-term impacts are still not known. The National Commission on the Deepwater Horizon Oil Spill and Offshore Drilling was set up to study what went wrong.

The Global Dependence of Transportation on Oil

Two-thirds of oil consumption is devoted to transportation, providing fuel for cars, trucks, trains and airplanes. For the United States and most developed societies, transportation is woven into the fabric of our lives, a necessity as central to daily operations as food or shelter. The concentration of oil reserves in a few regions or the world makes much of the world dependent on imported

energy for transportation. The rise in the price of oil in the last decade makes dependence on imported energy for transportation an economic as well as an energy issue. The United States, for example, now spends upwards of $350 billion annually on imported oil, a drain of economic resources that could be used to stimulate growth, create jobs, build infrastructure and promote social advances at home.

Coal

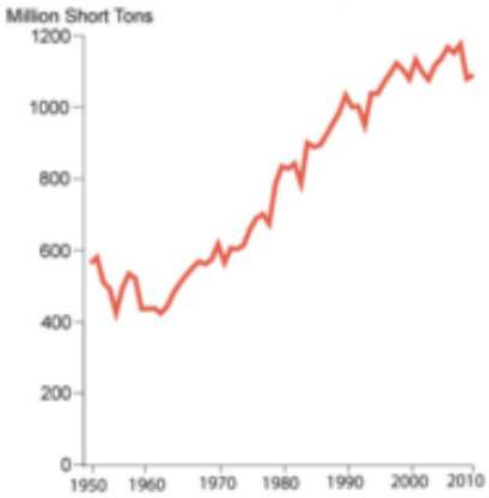


Figure 13.3.1. Historic U.S. Coal Production Graph shows U.S. Coal Production from 1950-2010. Source: U.S. Energy Information Administration

Unlike oil, **coal** is a solid. Due to its relatively low cost and abundance, coal is used to generate about half of the electricity consumed in the United States. Coal is the largest domestically produced source of energy. Coal production has doubled in the United States over the last sixty year (Figure 13.3.1). Current world reserves are estimated at 826,000 million tonnes, with nearly 30% of that in the United States. It is a major fuel resource that the United States controls domestically.

Coal is plentiful and inexpensive, when looking only at the market cost relative to the cost of other sources of electricity, but its extraction, transportation, and use produces a multitude of environmental impacts that the market cost does not truly represent. Coal emits sulfur dioxide, nitrogen oxide, and mercury, which have been linked to acid rain, smog, and health issues. Burning of coal emits higher amounts of carbon dioxide per unit of energy than the use of oil or natural gas. Coal accounted for 35% of the total United States emissions of carbon dioxide released into the Earth's atmosphere in 2010. Ash generated from combustion contributes to water contamination. Some coal mining has a negative impact on ecosystems and water quality, and alters landscapes and scenic views (such as with mountaintop mining).

There are also significant health effects and risks to coal miners and those living in the vicinity of coal mines. Traditional underground mining is risky to mine workers due to the risk of entrapment or death. Over the last 15 years, the U.S. Mine Safety and Health Administration has published the number of mine worker fatalities and it has varied from 18-48 per year. Twenty-nine miners died on April 6, 2010 in an explosion at the Upper Big Branch coal mine in West Virginia, contributing to the uptick in deaths between 2009 and 2010. In other countries, with less safety regulations, accidents occur more frequently. In May 2011, for example, three people died and 11 were trapped in a coalmine in Mexico for several days. There is also risk of getting **black lung disease** (pneumoconiosis). This is a disease of the lungs caused by the inhalation of coal dust over a long period of time**.** It causes coughing and shortness of breath. If exposure is stopped the outcome is good. However, the complicated form may cause shortness of breath that gets increasingly worse.



Figure 13.3.2. Mountaintop Removal Coal Mining in Martin County, Kentucky Photograph shows mountaintop coal removal mining in Martin County, Kentucky. Source: Flashdark.

Mountaintop mining (MTM), while less hazardous to workers, has particularly detrimental effects on land resources. MTM is a surface mining practice involving the removal of mountaintops to expose coal seams, and disposing of the associated mining waste in adjacent valleys. This form of mining is very damaging to the environment because it literally removes the tops of mountains, destroying the existing habitat. Additionally, the debris from MTM is dumped into valleys burying streams and other important habitat.

Natural Gas

Natural gas meets 20% of world energy needs and 25% of United States needs. **Natural gas** is mainly composed of methane (CH_4) and is a very potent greenhouse gas. There are two types of natural gas. **Biogenic gas** is found at shallow depths and arises from anaerobic decay of organic matter by bacteria, like landfill gas. **Thermogenic gas** comes from the compression of organic matter and deep heat underground. They are found with petroleum in reservoir rocks and with coal deposits, and these fossil fuels are extracted together.

Natural gas is released into the atmosphere from coal mines, oil and gas wells, and natural gas storage tanks, pipelines, and processing plants. These leaks are the source of about 25% of total U.S. methane emissions, which translates to three percent of total U.S. greenhouse gas emissions. When natural gas is produced but cannot be captured and transported economically, it is "flared," or burned at well sites, which converts it to CO_2. This is considered to be safer and better than releasing methane into the atmosphere because CO_2 is a less potent greenhouse gas than methane.

In the last few years a new reserve of natural gas has been identified: shale resources. The United States possesses 2,552 trillion cubic feet (Tcf) (72.27 trillion cubic meters) of potential natural gas resources, with shale resources accounting for 827 Tcf (23.42 tcm). As natural gas prices increased it has become more economical to extract the gas from shale. Figure 13.3.3 shows the past and forecasted U.S. natural gas production and the various sources. The current reserves are enough to last about 110 years at the 2009 rate of U.S. consumption (about 22.8 Tcf per year -645.7 bcm per year).

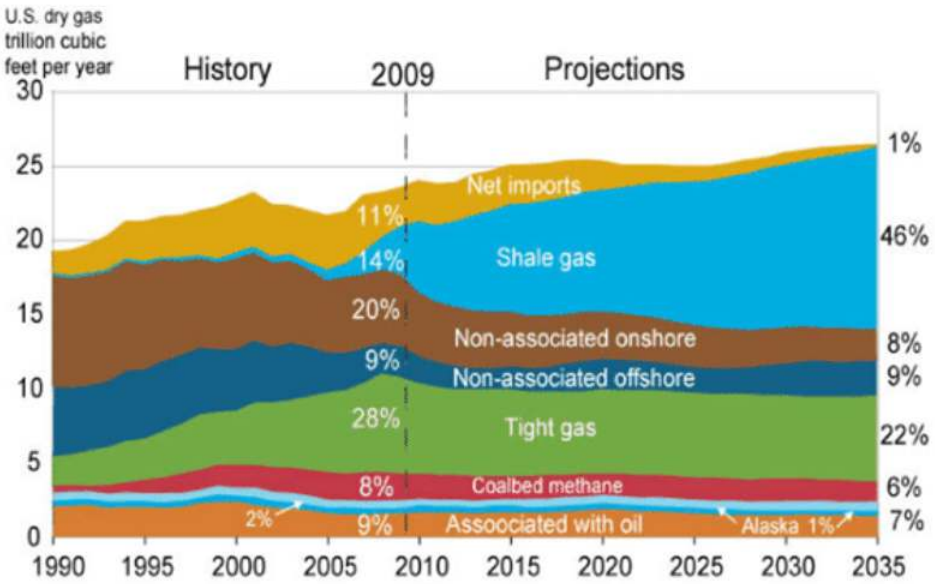


Figure 13.3.3. U.S. Natural Gas Supply, 1990-2035 Graph shows U.S. historic and projected natural gas production from various sources. Source: U.S. Energy Information Administration

Natural gas is a preferred fossil fuel when considering its environmental impacts. Specifically, when burned, much less carbon dioxide (CO_2), nitrogen oxides, and sulfur dioxide are omitted than from the combustion of coal or oil. It also does not produce ash or toxic emissions.

Natural gas production can result in the production of large volumes of contaminated water. This water has to be properly handled, stored, and treated so that it does not pollute land and water supplies. Extraction of shale gas is more problematic than traditional sources due to a process nicknamed **fracking,** or fracturing of wells, since it requires large amounts of water (Figure 13.3.4). The technique uses high-pressure fluids to fracture the normally hard shale deposits and release gas and oil trapped inside the rock. To promote the flow of gas out of the rock, small particles of solids are included in the fracturing liquids to lodge in the shale cracks and keep them open after the liquids are depressurized. The considerable use of water may affect the availability of water for other uses in some regions and this can affect aquatic habitats. If mismanaged, hydraulic fracturing fluid can be released by spills, leaks, or various other exposure pathways. The fluid contains potentially hazardous chemicals such as hydrochloric acid, glutaraldehyde, petroleum distillate, and ethylene glycol. The risks of fracking have been highlighted in popular culture in the documentary, Gasland (2010).

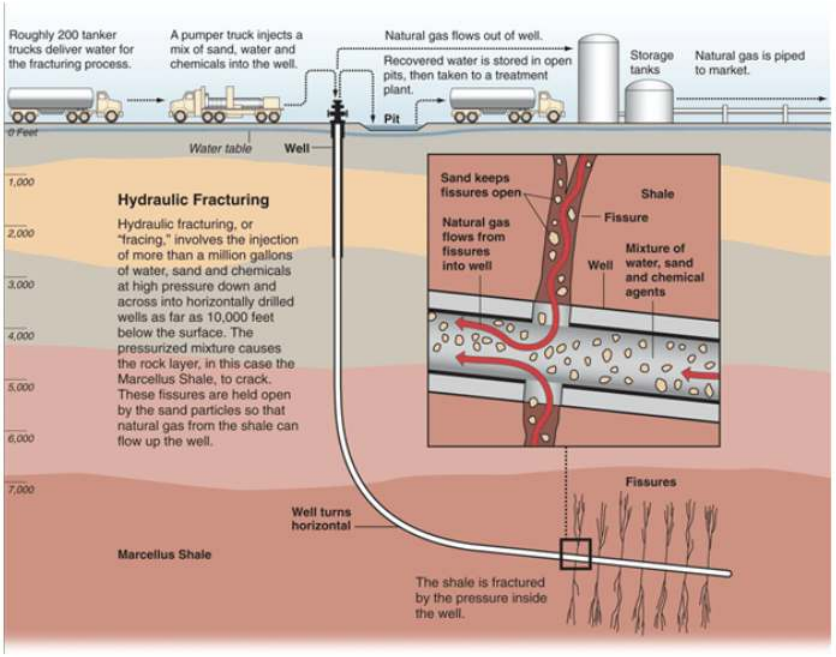


Figure 13.3.4. Graphic illustrates the process of hydraulic fracturing. Source: Al Granberg, ProPublica.

The raw gas from a well may contain many other compounds besides the methane that is being sought, including hydrogen sulfide, a very toxic gas. Natural gas with high concentrations of hydrogen sulfide is usually flared which produces CO_2, carbon monoxide, sulfur dioxide, nitrogen oxides, and many other compounds. Natural gas wells and pipelines often have engines to run equipment and compressors, which produce additional air pollutants and noise.

Contributions of Coal and Natural Gas to Electricity Generation

At present the fossil fuels used for electricity generation in the US are predominantly coal (44%) and natural gas (23%); petroleum accounts for approximately 1%. Coal electricity traces its origins to the early 20th Century, when it was the natural fuel for steam engines given its abundance, high energy density and low cost. gatural Gas is a later addition to the fossil electricity mix, arriving in significant quantities after World War II and with its greatest growth since 1990. Of the two fuels, coal emits almost twice the carbon dioxide as natural gas for the same heat output, making it significantly greater contributor to global warming and climate change.

The Future of Natural Gas and Coal

The future development of coal and natural gas depend on the degree of public and regulatory concern for carbon emissions, and the relative price and supply of the two fuels. Supplies of coal are abundant in the United States, and the transportation chain from mines to power plants is well established. The primary unknown factor is the degree of public and regulatory pressure that will be placed on carbon emissions. Strong regulatory pressure on carbon emissions would favor retirement of coal and addition of natural gas power plants. This trend is reinforced by the recent dramatic expansion of shale gas reserves in the United States due to advances in drilling technology. Shale natural gas production has increased 48% annually in the years 2006 – 2010, with more increases expected. Greater United States production of shale gas will gradually reduce imports and could eventually make the United States a net exporter of natural gas.

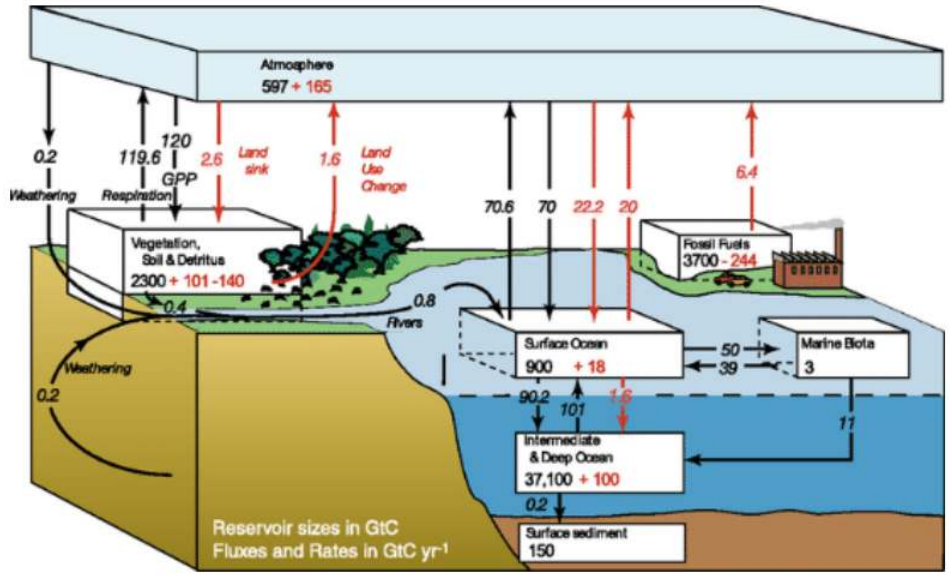


Figure 13.3.5. Global Carbon Cycle, 1990s The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr–1: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red. Source: Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, figure 7.3

Nuclear Power

Nuclear power is energy released from the radioactive decay of elements, such as uranium, which releases large amounts of energy. Nuclear power plants produce no carbon dioxide and, therefore, are often considered an **alternative fuel** (fuels other than fossil fuels)**.** Currently, world production of electricity from nuclear power is about 19.1 trillion KWh, with the United States producing and consuming about 22% of that. Nuclear power provides about 9% of the electricity in the United States (Figure 13.3.7).

There are environmental challenges with nuclear power. Mining and refining uranium ore and making reactor fuel demands a lot of energy. Also, nuclear power plants are very expensive and require large amounts of metal, concrete, and energy to build. The main environmental challenge for nuclear power is the wastes including uranium mill tailings, spent (used) reactor fuel, and other radioactive wastes. These materials have long radioactive half-lives and thus remain a threat to human health for thousands of years. The **half life** of a radioactive element is the time it takes for 50% of the material to radioactively decay. The U.S. Nuclear Regulatory Commission regulates the operation of nuclear power plants and the handling, transportation, storage, and disposal of radioactive materials to protect human health and the environment.

By volume**,** the waste produced from mining uranium, called **uranium mill tailings,** is the largest waste and contains the radioactive element radium, which decays to produce radon, a radioactive gas. **High-level radioactive waste** consists of used nuclear reactor fuel. This fuel is in a solid form consisting of small fuel pellets in long metal tubes and must be stored and handled with multiple containment, first cooled by water and later in special outdoor concrete or steel containers that are cooled by air. There is no long-term storage facility for this fuel in the United States.

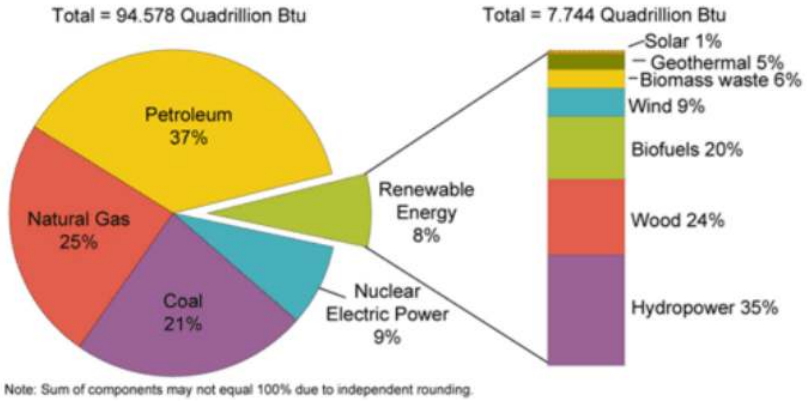


Figure 13.3.7. U.S. Energy Consumption by Energy Source, 2009 Renewable energy makes up 8% of U.S. energy consumption. Source: U.S. Energy Information Administration

There are many other regulatory precautions governing permitting, construction, operation, and decommissioning of nuclear power plants due to risks from an uncontrolled nuclear reaction. The potential for contamination of air, water and food is high should an uncontrolled reaction occur. Even when planning for worst-case scenarios, there are always risks of unexpected events. For example, the March 2011 earthquake and subsequent tsunami that hit Japan resulted in reactor meltdowns at the Fukushima Daiichi Nuclear Power Station, causing massive damage to the surrounding area.

Debating Nuclear Energy

From a sustainability perspective, nuclear electricity presents an interesting dilemma. On the one hand, nuclear electricity produces no carbon emissions, a major sustainable advantage in a world facing anthropogenic climate change. On the other hand, nuclear electricity produces dangerous waste that i) must be stored out of the environment for thousands of years, ii) can produce bomb-grade plutonium and uranium that could be diverted by terrorists or others to destroy cities and poison the environment, and iii) threatens the natural and built environment through accidental leaks of long-lived radiation. Thoughtful scientists, policy makers, and citizens must weigh the benefit of this source of carbon-free electricity against the environmental risk of storing spent fuel, the societal risk of nuclear proliferation, and the impact of accidental or deliberate release of radiation. There are very few examples of humans having the power to permanently change the dynamics of the earth. Global climate change from carbon emissions is one example, and radiation from the explosion of a sufficient number of nuclear weapons is another. Nuclear electricity touches both of these opportunities, on the positive side for reducing carbon emissions and on the negative side for the risk of nuclear proliferation.

Nuclear electricity came on the energy scene remarkably quickly. Following the development of nuclear technology at the end of World War II for military ends, nuclear energy quickly acquired a new peacetime path for inexpensive production of electricity. Eleven years after the end of World War II, a very short time in energy terms, the first commercial nuclear reactor produced electricity at Calder Hall in Sellafield, England. The number of nuclear reactors grew steadily to more than 400 by 1990, four years after the Chernobyl disaster in 1986 and eleven years following Three Mile Island in 1979. Since 1990, the number of operating reactors has remained approximately flat, with new construction balancing decommissioning due to public and government reluctance to proceed with nuclear electricity expansion plans.

The outcome of this debate will determine whether the world experiences a nuclear renaissance that has been in the making for several years. The global discussion has been strongly impacted by the unlikely nuclear accident in Fukushima, Japan in March 2011. The Fukushima nuclear disaster was caused by an earthquake and tsunami that disabled the cooling system for a nuclear energy complex consisting of operating nuclear reactors and storage pools for underwater storage of spent nuclear fuel ultimately causing a partial meltdown of some of the reactor cores and release of significant radiation. This event, 25 years after Chernobyl, reminds us that safety and public confidence are especially important in nuclear energy; without them expansion of nuclear energy will not happen.

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13.4: Coal

Coal is a combustible black or brownish-black sedimentary rock with a high amount of carbon and hydrocarbons. Coal is classified into four main types, or ranks depending on the types and amounts of carbon present and on the amount of heat energy the coal can produce, including anthracite, bituminous, subbituminous, and lignite (highest to lowest ranked, pictured in Figure 13.4.1). For us to use the potential energy stored in coal, it first must be mined from the ground. This process in itself uses a great deal of resources and has its own environmental impacts. Coal then typically undergoes processing to make it suitable for use in **coal-fire power plants**. Finally, the processed coal is burned in these power plants, and the kinetic energy released from its combustion is harnessed for electricity generation or other purposes. We will investigate each of these steps individually below.

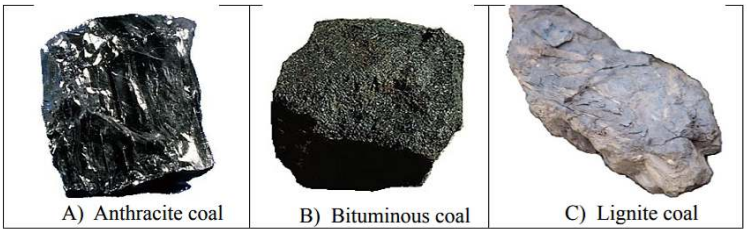


Figure 13.4.1: Different types of coal. Images obtained from Wikimedia Commons.

4.3.1: Coal Mining and Processing, and Electricity Generation

There are two primary methods of coal mining: **strip mining** and **underground mining**. Strip-, or surface-, mining uses large machines to remove the soil and layers of rock known as **overburden** to expose coal seams. It is typically used when the coal is less than 200 feet underground. **Mountaintop removal** is a form of surface mining where the tops of mountains are blasted with dynamite and removed to access coal seams. After the mining is finished, the disturbed area can be re-covered with topsoil, and the area is replanted. However, the topography of the mountain is permanently altered.

Underground mining, sometimes called deep mining, is used when the coal is several hundred feet below the surface. 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.

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**.

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. 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.

Once at the power plant, coal is first pulverized into a fine powder then mixed with hot air and blown into a **furnace**, allowing for the most complete combustion and maximum heat possible. 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 13.4.2 below is a schematic diagram showing a typical layout of a coal-fire power plant. You can also watch a short video of a virtual tour of a coal power plant at the URL provided below.

Coal Power Plant Virtual Tour Video https://www.youtube.com/watch?v=2IKECt4Y3RI

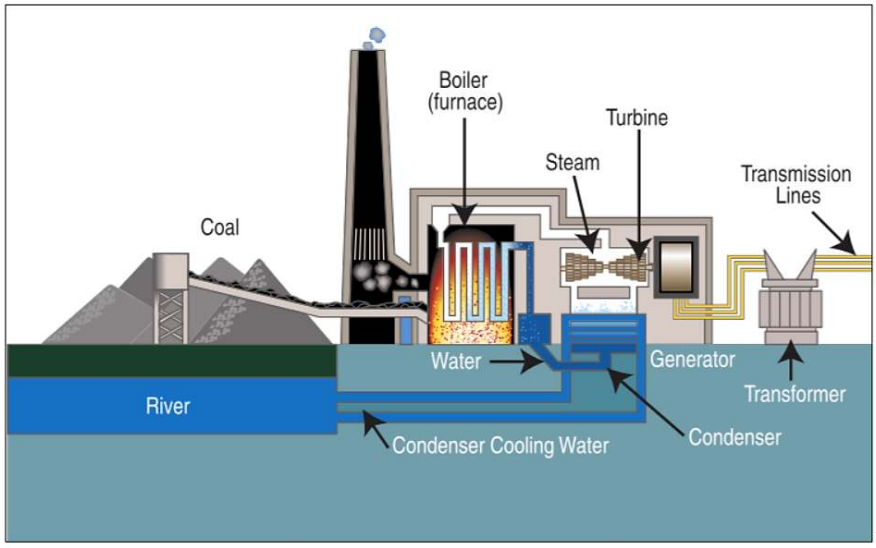


Figure 13.4.2: Diagram of a typical steam-cycle coal power plant (proceeding from left to right). Image by US Tennessee Valley Authority – Public domain. www.tva.com

4.3.2: Impacts of coal mining and burning

Impacts of coal mining on the environment

A majority of the coal mined in the United States (about 66%) is from surface, or strip mines which leave highly visible impacts at the surface. Strip mining operations generally involve removing soils, rock, and other material to access shallow deposits of coal and therefore leave permanent scars on the landscape. It also involves the destruction of substantial amounts of forests and other ecosystems, destroying natural habitats and threatening biodiversity.

Mountaintop removal, the extreme form of strip mining, has affected large areas of the Appalachian Mountains in West Virginia and Kentucky. The tops of mountains are removed using a combination of explosives and mining equipment and the material is deposited into nearby valleys. This technique not only alters the landscape (Figure 13.4.3) but affects the health and quality of nearby streams by depositing rocks, dirt, and pollutants that can harm aquatic wildlife. While mountaintop removal mining has existed since the 1970s, its use became more widespread and controversial beginning in the 1990s. U.S. laws require that dust and water runoff from areas affected by coal mining operations be controlled, and that the area be **reclaimed**, and returned to close to its original condition.



Figure 13.4.3: A) Strip mine for lignite coal at Garzweiler near Koln, Germany. Image from Wikimedia commons https://commons.wikimedia.org/wiki/F...strip.mine.jpg B) Mountaintop removal in Eunice WV, photo by Roston, obtained from https://commons.wikimedia.org/wiki/F...niceblast3.JPG

One of the largest environmental impacts of underground mining may be the **methane** gas that must be vented out of mines to make the mines a safe place to work. Methane is a **greenhouse gas**, meaning that it enhances the greenhouse effect naturally occurring in our atmosphere, and contributes to global warming and global climate change. Its global warming potential, or relative capacity to produce the greenhouse effect, is higher than that of carbon dioxide (see chapter 7). Other impacts of underground mining include ground collapse above mine tunnels and draining of acidic water from abandoned mines into nearby streams. Acidic

water lowers the pH (resulting in increased **acidity**), which is detrimental to aquatic organisms. This **acid mine drainage** is an environmental impact associated with both underground mining and strip mining.

Impacts of coal burning on the environment and human health

In the United States and most of the world, most of the coal consumed is used as a fuel to generate electricity. Burning coal produces emissions such as **sulfur dioxide** (SO_2) and **nitrogen oxides** (NO_x) that are associated with acid rain (more on this in chapter 6). **Carbon dioxide** (CO_2), another emission resulting from burning coal, is a major greenhouse gas that is associated with global warming (see chapter 7).

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 (see chapter 6). 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. Pollution leaching from ash storage and landfills into groundwater and the rupture of several large impoundments of ash are environmental concerns.

Burning coal produces emissions that also impact human health. Emissions such as sulfur dioxide (SO_2), nitrogen oxides (NO_x) and particulates contribute to respiratory illnesses. Particulates also contribute to a condition among coal miners and other coal workers known as coal workers' pneumoconiosis (CWP) or black lung disease, which results from long exposure to coal dust. Inhaled coal dust progressively builds up in the lungs and is unable to be removed by the body; this leads to inflammation, fibrosis, and in worse cases, tissue death (necrosis).

Coal is the largest source of **mercury** and also a source of other **heavy metals**, many of which have been linked to both neurological and developmental problems in humans and other animals. Mercury concentrations in the air usually are low and of little direct concern. However, when mercury enters water, either directly or through deposition from the air, biological processes transform it into **methylmercury**, a highly toxic chemical that accumulates in fish and the animals (including humans) that eat fish.

4.3.3: Reducing the environmental impacts of coal use

Regulations such as the **Clean Air Act** and the **Clean Water Act** require industries to reduce pollutants released into the air and water. Below are some actions that have been taken to reduce the negative impacts of coal on human and environmental health:

- **Clean coal technology**: Industry has found several ways to reduce sulfur, NO_x, and other impurities from coal before burning.
- Coal consumers have shifted toward greater use of low sulfur coal.
- Power plants use **scrubbers**, to clean SO_2, NO_x, particulate matter, and mercury from the smoke before it leaves their smokestacks. In addition, industry and the U.S. government have cooperated to develop technologies that make coal more energy-efficient so less needs to be burned.
- Research is underway to address emissions of carbon dioxide from coal combustion. **Carbon capture & sequestration** separates CO_2 from emissions sources and recovers it in a concentrated stream. The CO_2 can then be sequestered, which puts CO_2 into storage, possibly underground, where it will remain permanently (see chapter 7)
- Reuse and recycling can also reduce coal's environmental impact. Land that was previously used for coal mining can be reclaimed and used for airports, landfills, and golf courses. Waste products captured by scrubbers can be used to produce products like cement and synthetic gypsum for wallboard.

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13.5: Oil

Petroleum Oil is currently the most widely used fossil fuel and accounts for about one third of global energy consumption. Unlike coal, which is primarily used as a fuel for electricity generation, oil is primarily used as a fuel for **transportation**. Oil is also used to manufacture plastics and other synthetic compounds ubiquitous to our everyday life. **Crude** (unprocessed) oil varies greatly in appearance depending on its composition. It is usually black or dark brown (although it may be yellowish, reddish, or even greenish). In the reservoir it is usually found in association with natural gas, which being lighter forms a gas cap over the oil.

Oil is made up of hydrocarbons which are molecules that contain hydrogen and carbon in various lengths and structures, from straight chains to branching chains to rings. Hydrocarbons contain a lot of energy and many of the things derived from crude oil like gasoline, diesel fuel, paraffin wax and so on take advantage of this energy.

4.4.1: Extraction

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. 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 oil producers are required to take precautions to prevent pollution, spills, and significant changes to the ocean environment. Offshore rigs are designed to withstand hurricanes. Offshore production is much more expensive than land-based production. When offshore oil wells are no longer productive enough to be economical, they are sealed and abandoned according to applicable regulations.

4.4.2: Processing and Refining

When extracted, crude oil consists of 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 at a **refinery** (Figure 13.5.1). All refineries perform three basic steps: separation, conversion, and treatment in the processing and refining of crude oil.



Figure 13.5.1: Tesoro Corporation Oil Refinery in Anacortes, Washington. Photo by Walter Siegmund. https://commons.wikimedia.org/wiki/O...nery_31904.JPG

During **separation**, the various products (hydrocarbons) are separated in to different components (called *fractions*), by taking advantage of the differences in boiling temperature of the components. This process is called *fractional distillation* and involves heating up the crude, letting it vaporize and then condensing the vapor. The lightest components have the lowest boiling temperature and rise to the top while the heaviest which also have the highest boiling temperature remain at the bottom.

Conversion is the chemical processing in which some of the fractions 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 (e.g., WD-40, 10W-40, 5W-30, etc.), heating oil and many others. The products are stored on-site 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. 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 (Figure 13.5.2). Other products include diesel fuel and heating oil, jet fuel, petrochemical feedstocks, waxes, lubricating oils, and asphalt.

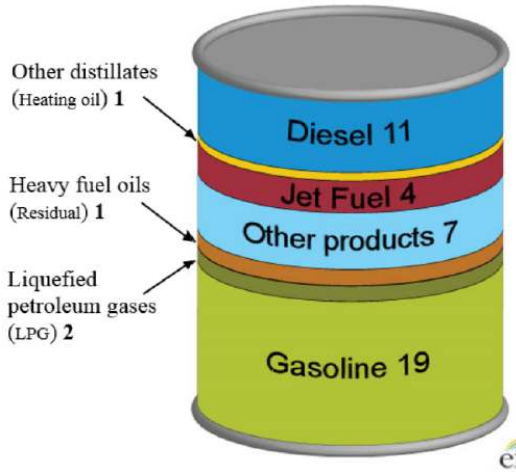


Figure 13.5.2: Main products (measured in gallons) made from a barrel of crude oil, 2013. Source: U.S. Energy information administration http://www.eia.gov/energyexplained/i...?page=oil_home

4.4.3: Fracking for oil

Hydraulic fracturing, informally referred to as "fracking," is an oil well development process that typically involves injecting water, sand, and chemicals under high pressure into a bedrock formation via the well. This process is intended to create new fractures in the rock as well as increase the size, extent, and connectivity of existing fractures. Hydraulic fracturing is a well-stimulation technique used commonly in low-permeability rocks like tight sandstone, shale, and some coal beds to increase oil flow to a well from petroleum-bearing rock formations (Figure 13.5.3).

Energy development often requires substantial amounts of water, and hydraulic fracturing is no exception. Water is needed not only for the traditional drilling process, but also for the actual fracturing as well. Water is first mixed with chemicals and fine sands, then pumped at extremely high pressure into the shale rock to fracture it, forming pathways for the oil and gas to reach the well. The water is then recovered, along with the oil and gas.

There are concerns regarding the potential contamination of fresh groundwater resources from oil and gas extraction wells that use hydraulic fracturing; either from the petroleum resource being produced or from the chemicals introduced in the fracturing process. 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, **volatile organic compounds** (VOCs) and hazardous air pollutants such as benzene, toluene, ethylbenzene and xylene. 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.

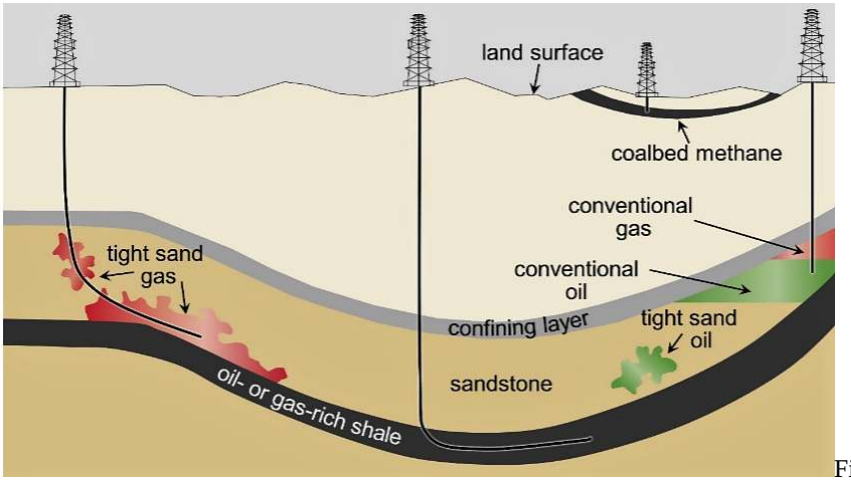


Figure 13.5.3: Schematic cross-section of general types of oil and gas resources and the orientations of production wells used in hydraulic fracturing. Source: US EPA (Public Domain)

4.4.4: Environmental Impacts of Oil

Burning petroleum oil products releases emission such as carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate material all of which are air pollutants that impact the environment as well as human health (see more on air pollution in Chapter 6). Petroleum also emits carbon dioxide which is a greenhouse gas Exploring and drilling for oil may disturb 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.

Human-caused **oil spills** in rivers and oceans harm ecosystems. Natural oil seepages do occur and may be a significant source of oil that enters the environment globally, but they are slow, small, and spread out over large areas, and the ecosystem has adapted to them. Spills from tankers or well spills have more catastrophic impacts. The quantity of oil spilled during accidents has ranged from a few hundred tons to several hundred thousand tons but even small spills have been shown to have a great impact on ecosystems.

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. The amount of oil spilled from ships dropped significantly during the 1990s partly because new ships were required to have a double-hull lining to protect against spills.

Leaks also happen when we use petroleum products 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 products 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, petroleum products 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.

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13.6: Natural Gas

4.5.1: Introduction

Crude oil is frequently found in reservoirs along with natural gas. In the past, natural gas was either burned or allowed to escape into the atmosphere. Now, technology has been developed to capture the natural gas and either reinject it into the well or compress it into **liquid natural gas** (LNG).

Natural gas is predominately composed of methane (CH_4). Some of the gases that are produced along with methane, such as butane and propane (by-products), are separated and cleaned at a gas processing plant. The by-products, once removed, are used in a number of ways. For example, propane can be used for cooking on gas grills. Natural gas withdrawn from a well may contain liquid hydrocarbons and nonhydrocarbon gases. This is called "wet" natural gas. The natural gas is separated from these components near the site of the well or at a processing plant. The gas is then considered "dry" and is sent through pipelines to a local distribution company, and, ultimately, to the consumer.

Most of the natural gas consumed in the United States is produced in the United States. Some is imported from Canada and shipped to the United States in pipelines. A small amount of natural gas is shipped to the United States as LNG. We can also use machines called **digesters** that turn today's organic material (plants, animal wastes, etc.) into natural gas through the process of anaerobic decomposition. This process replaces waiting for millions of years for the gas to form naturally. The natural gas produced by these digesters is not a fossil fuel, but is rather a renewable source of bioenergy (see chapter 5).

4.5.2: Fracking for Gas

Conventional natural gas is found in permeable reservoirs, typically composed of sandstone or limestone, where extraction is relatively straightforward because the gas generally flows freely. Unconventional gas is found in rocks with extremely low permeability, which makes extracting it much more difficult. Such gas is extracted by employing so-called “unconventional” techniques such as hydraulic fracturing (fracking), which has been in use since the late 1940s. In recent decades, fracking technology has greatly improved, and its use has been expanded. The process of fracking for gas is very similar to that of fracking for oil, and the environmental impacts are similar also.

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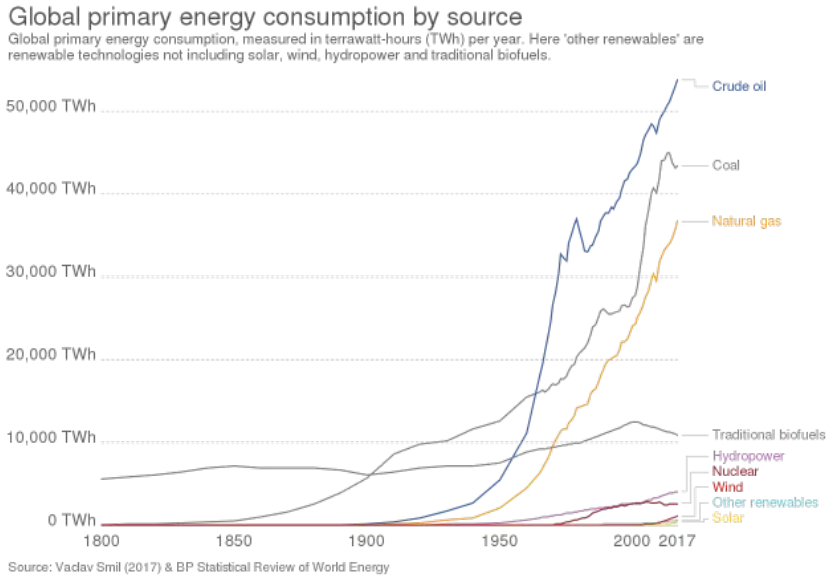
13.7: Energy from Fossil Fuels

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 13.7.1). 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%; figure13.7.1).

Table 13.7.1**:** 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).



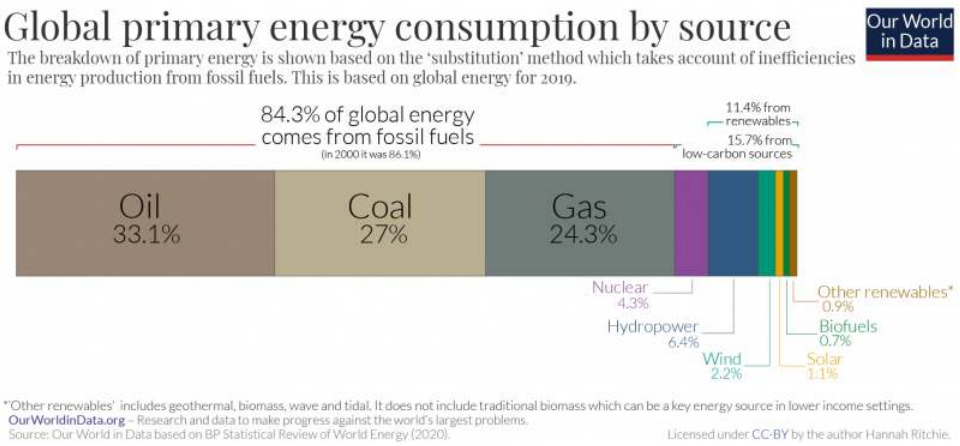


Figure 13.7.1**:** The top graph shows global energy consumption by source shows energy consumption in terrawatt-hours (TWh) on the y-axis and time in years (1800-2017) on the X-axis. The bottom graph shows the percentage that each energy source contributes to global energy consumption in 2019. Global 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).

Generating Electricity from Coal

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 coal reserves 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.

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. 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 13.7.2). 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 13.7.2**:** A freight train loaded with coal briquettes, formed from compressed coal dust, in Morwell, Victoria, Australia. Image and caption (modified) by CSIRO (CC-BY).

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 13.7.3). 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.

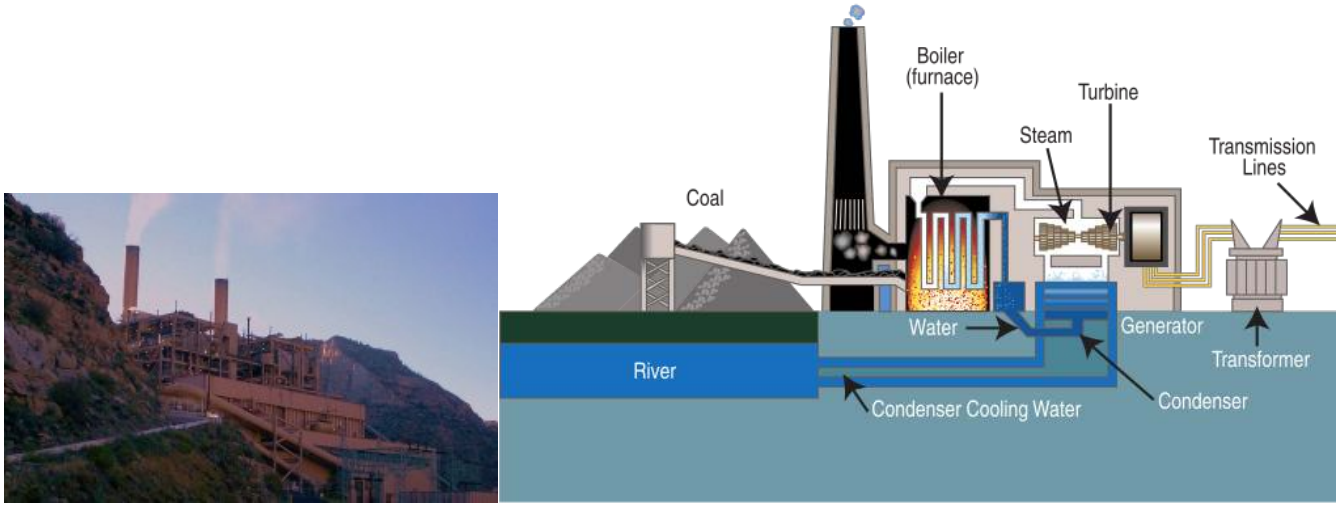
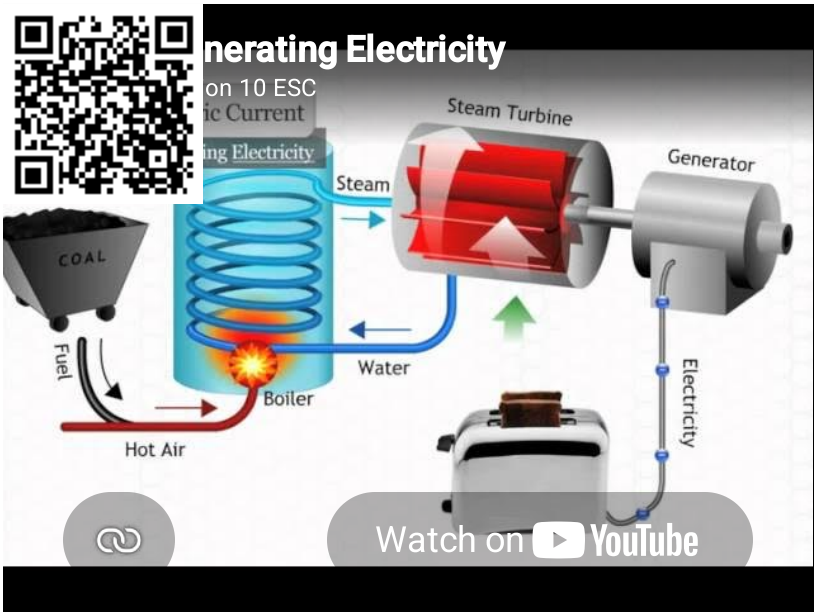


Figure 13.7.3**:** Left: Coal power plant in Helper, Utah. Right: Diagram of a typical steam-cycle coal power plant (proceeding from left to right). Coal enters the boiler (furnace), where it is burned. This boils water, producing steam. The steam turns a turbine, powering a generator. The resultant 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).

Coal is plentiful and inexpensive, when looking only at the market cost relative to the cost of other sources of electricity, but its extraction, transportation, and use produces a multitude of environmental impacts that the market cost does not truly represent. Coal emits sulfur dioxide, nitrogen oxide, and mercury, which have been linked to acid rain, smog, and health issues. Burning of

coal emits higher amounts of carbon dioxide per unit of energy than the use of oil or natural gas. Coal accounted for 35% of the total United States emissions of carbon dioxide released into the Earth's atmosphere in 2010. Ash generated from combustion contributes to water contamination.

This video shows how heat energy can be used to generate electricity.



Generating Electricity from Oil and Natural Gas

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 (figure13.7.4). 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.

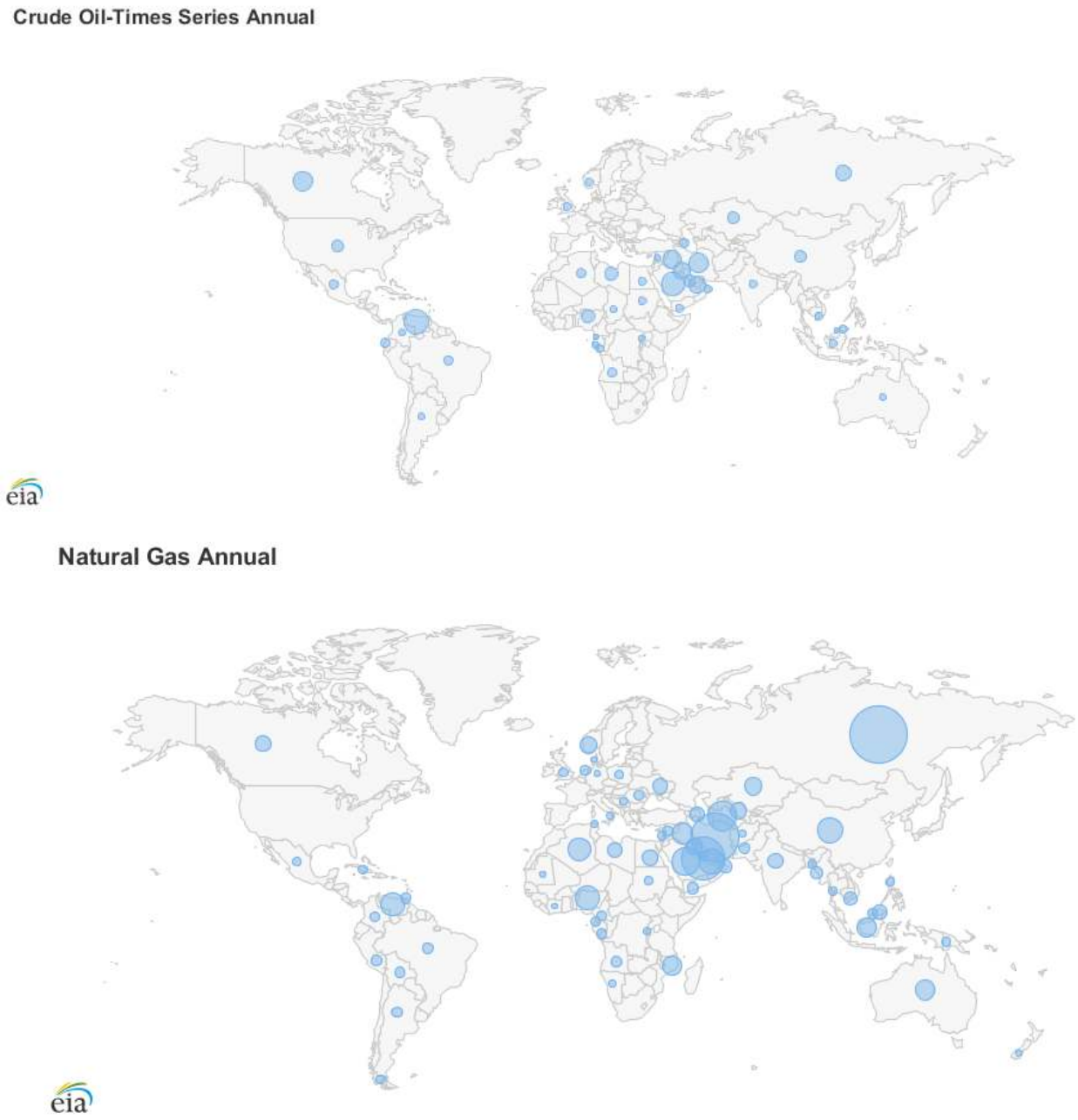


Figure 13.7.4**:** Global reserves of oil (top) and natural gas (bottom) by country in 2017 and 2020, respectively. The blue circle in each country is scaled to the size of the reserve. Both fossil fuels are abundant in the Middle East. Russia also has a rich supply of natural gas. Images from EIA (public domain).

The major holder of oil reserves is the **Organization of Petroleum Exporting Countries,** (OPEC). As of 2018, there were 15 member countries in OPEC: Algeria, Angola, Congo, Ecuador, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela. OPEC attempts to influence the amount of oil available to the world by assigning a production quota to each member except Iraq, for which no quota is presently set.

Overall compliance with these quotas is mixed since the individual countries make the actual production decisions. All of these countries have a national oil company but also allow international oil companies to operate within their borders. They can restrict the amounts of production by those oil companies. Therefore, the OPEC countries have a large influence on how much of world demand is met by OPEC and non-OPEC supply.

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.

Natural Gas Power Plants

Natural gas is burned to produce electricity following the same general process used in a coal power plant (figure 13.7.5). Oil is occasionally used to generate electricity as well.

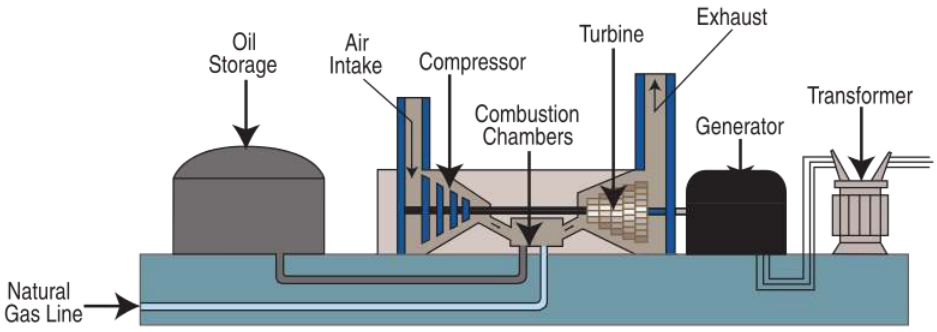


Figure 13.7.5**:** This combustion chamber burns either natural gas or oil. Fuel flows through a natural gas line or from oil storage into the combustion chamber. Air passes through the air intake and is compressed in the compressor. Natural gas and compressed air are mixed with compressed air in the 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).

The Global Dependence of Transportation on Oil

Two-thirds of oil consumption is devoted to transportation, providing fuel for cars, trucks, trains and airplanes. For the United States and most developed societies, transportation is woven into the fabric of our lives, a necessity as central to daily operations as food or shelter. The concentration of oil reserves in a few regions or the world makes much of the world dependent on imported energy for transportation. The rise in the price of oil in the last decade makes dependence on imported energy for transportation an economic as well as an energy issue. The United States, for example, now spends upwards of $350 billion annually on imported oil, a drain of economic resources that could be used to stimulate growth, create jobs, build infrastructure and promote social advances at home.

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 13.7.6).

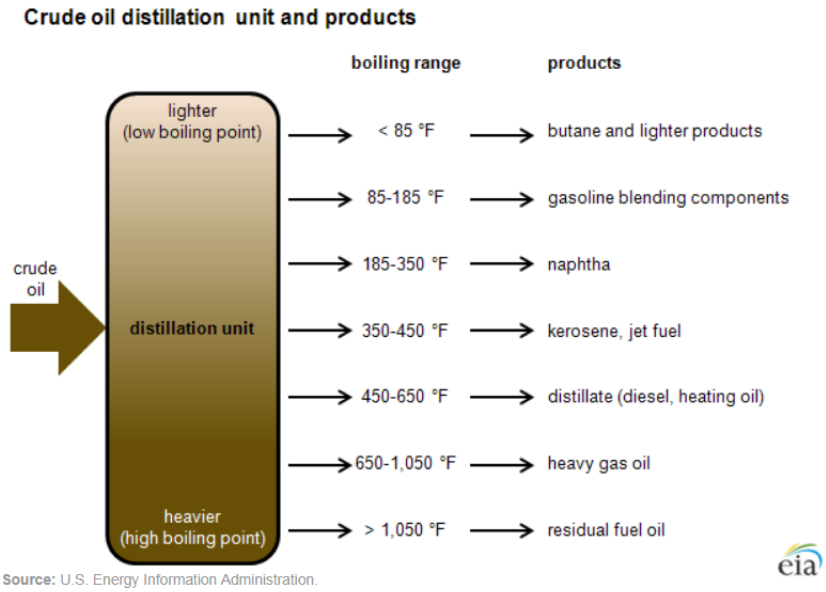


Figure 13.7.6**:** The process of fractional distillation involves heating crude oil and allowing the components to cool. As they move up the distillation column, they condense at different levels based on their boiling points. The heaviest compounds have the highest boiling points and condense at the 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).



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 13.7.7). 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.

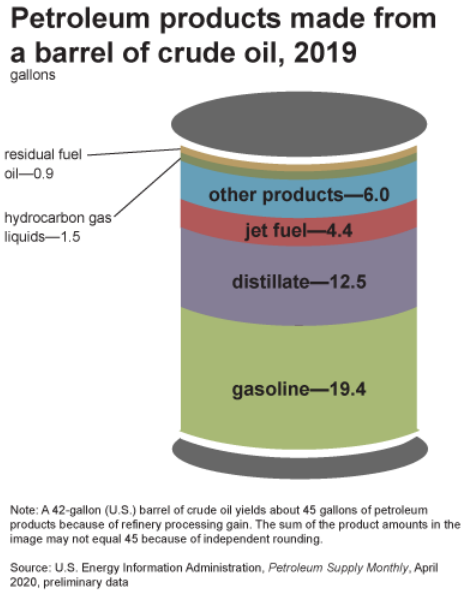


Figure 13.7.7**:** Main products (measured in gallons) made from a barrel of crude oil in 2019. These include residual fuel oil (0.9 gallons), hydrocarbon gas (1.5), other products (6.0), jet fuel (4.4), distillate (12.5), and gasoline (19.4). Note: A 42-gallon (U.S.) barrel of crude oil yields about 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).

Oil refining is one of top sources of air pollution in the United States for volatile organic hydrocarbons and toxic emissions, and the single largest source of carcinogenic benzene. When petroleum is burned as gasoline or diesel, or to make electricity or to power boilers for heat, it produces a number of emissions that have a detrimental effect on the environment and human health:

- Carbon dioxide (CO_2) is a greenhouse gas and a source of climate change.
- Sulfur dioxide (SO_2) causes acid rain, which damages plants and animals that live in water, and it increases or causes respiratory illnesses and heart diseases, particularly in vulnerable populations like children and the elderly.
- Nitrous oxides (NO_x) and Volatile Organic Carbons (VOCs) contribute to ozone at ground level, which is an irritant and causes damage to the lungs.
- Particulate Matter (PM) produces hazy conditions in cities and scenic areas, and combines with ozone to contribute to asthma and chronic bronchitis, especially in children and the elderly. Very small, or “fine PM,” is also thought to penetrate the respiratory system more deeply and cause emphysema and lung cancer.
- Lead can have severe health impacts, especially for children.

Transportation of Oil and Natural Gas

Most of the production of oil and natural gas occurs in remote areas, while most consumption is in densely populated areas. Consequently, enormous quantities of petroleum and its refined products are transported over great distances, mostly by overland pipelines, railroads, and trucks. 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. On the global scale, most petroleum and its refined products are transported by oceanic tankers and overland pipelines. Local distribution systems involve smaller tankers, barges, pipelines, railroads, and trucks. There is a risk of accidental spillage

from all of these means of transportation. Some of the spills have been spectacular in their volume and environmental damage. In addition, petroleum is discharged into the environment by many smaller sources, which sum to a large cumulative amount.

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 13.7.8). 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 13.7.8**:** 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).

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 Spills

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 onto land are relatively common. Between 1989 and 1995, about 3,500 spills per year were reported in Canada – most all were relatively small, although by law they must be reported (Environment Canada, 1998). About 42% of the spills occurred in the vicinity of production wells, while 29% were from pipelines, and 16% from tanker trucks. During that period, up to 140-thousand t

of oil was spilled per year in petroleum-producing areas, due to accidental losses and well blowouts. In another study of the period 2000 to 2011, a total of 1,047 spills were reported from oil or gas pipelines in Canada (Kheraj, 2013).

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.

Oil spills can result from supertanker accidents such as the accidental grounding of 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. A significant amount of the petroleum extracted in the United States is mined in northern Alaska, from where a 1,280 km pipeline carries it south to the port of Valdez. The oil is then transported to markets in the western U.S. by a fleet of supertankers. The first part of the oceanic passage runs through a narrow shipping channel in Prince William Sound. Before the Exxon Valdez accident in March, 1989, tankers had navigated that passage about 16-thousand times. However, the Exxon Valdez, the newest tanker in the Exxon fleet, was steered onto a submerged reef, resulting in a spill of 36-thousand tonnes of its 176-thousand tonnes load of petroleum. About 40% of the spill washed onto shoreline habitat of Prince William Sound, while 25% was carried out of the sound by currents, and 35% evaporated at sea. Less than 10% was recovered or burned at sea.

The environmental damage was compounded by a lack of preparedness by industry and government for dealing with an oil-spill emergency. Essential equipment for containment and oil recovery was not immediately available, and it took too long to mobilize trained personnel. Consequently, despite favorable sea conditions during the first critical days after the grounding, few effective oil-spill countermeasures were mounted. Not until the second day of the spill was it possible to off-load unspilled petroleum from the Exxon Valdez to another tanker, and not until the third day were floating booms deployed to contain part of the spill. Unfortunately, a gale developed on the fourth day, making it impossible to contain or recover spilled petroleum, which then became widely dispersed. The region around Prince William Sound is famous for its spectacular scenery and large populations of wildlife. Some ecological communities and species were severely damaged by the oil spill. However, controversies have arisen about both the poor understanding of some ecological effects, and the role of science and scientists in sorting out legal and political aspects of the disaster (Holloway, 1996; Weins, 1996). For a long time, some scientists were prohibited from sharing their information because of legal needs for confidentiality. Controversies arose among scientists, environmental advocates, and other interest groups about the scale and intensity of some of the reported damages. About 1,900 km of shoreline habitat was oiled to some degree. A survey found that 140 km was “heavily oiled,” meaning there was at least a 6 m wide oiled zone. Another 93 km were “moderately oiled” (3-6 m wide zone), 323 km were “lightly oiled” (3 m wide), and the rest “very lightly oiled” (< 10% cover of oil). Overall, about 20% of the shoreline of the Sound, plus 14% of beaches on the nearby Kenai Peninsula and Kodiak Island, suffered some degree of oiling. A heroic and extremely expensive effort was undertaken to clean up some of the pollution from oiled beaches. About 11-thousand people were involved, costing the Exxon corporation about US$2.5 billion. The U.S. government spent an additional US$154 million. Residues were removed from heavily oiled beaches by machines and people wielding shovels and bags. Other places were cleaned by pressurized streams of hot or cold water. On some beaches, people actually wiped oiled rocks with absorbent cloths, a procedure that was ironically referred to as “rock polishing”.

These cleanup efforts helped greatly, and they were aided by natural processes, especially winter storms and microbial degradation of residues. Consequently, the amount of residues on beaches declined rapidly in the years following the spill. One survey of 28 polluted sites found an average of 37% surface oil cover in the first post-spill summer of 1989, but less than 2% in 1990. Another survey in 1991, after two post-spill winters and three summers, found that fewer than 2% of the beaches still had visible surface residues, compared with 20% in the first summer after the spill. However, subsurface residues still existed in many places. Initially, severe damage was caused to the seaweed-dominated intertidal zone of affected coastlines. These effects were made worse by certain cleanup methods, particularly washing with pressurized hot water. Fortunately, much of this damage proved to be short term, and by the end of 1991 a substantial recovery of seaweeds and invertebrates had begun. However, there were lingering effects on community structure, and vestiges of oil were still present 15 years later at some sites.



Figure 13.7.9**:** The top photo shows a heavily oiled beach on Green Island, Prince William Sound, soon after the Exxon Valdez disaster in 1989. The site was cleaned with warm-water washing in 1989, and then manually in 1990. In 1990 and 1991, it was treated with fertilizer to enhance microbial breakdown of the petroleum residues. The bottom photo shows the improved condition of the same beach in 1992, as a result of the natural and managed cleanups. Although little visible damage occurs on the surface, there are hydrocarbon residues deeper in the substrate. Source: Exxon Corporation.

Sea otters (*Enhydra lutris*) were the hardest-hit marine mammals. More than 3,500 otters were killed by oiling, out of a population of 5-10-thousand. A total of 357 oiled sea otters were captured and treated, of which 223 survived and were released or placed in zoos. Seabirds are very abundant in the region, particularly so in the autumn when certain species aggregate there during their southern migration. At that time, about 10-million seabirds may inhabit the Sound. Fortunately, the Exxon Valdez disaster happened in late winter, but there were still about 600-thousand seabirds present. About 36-thousand dead birds were found, but many additional corpses sank or drifted out to sea, and the total mortality may have been 375-435-thousand seabirds. About 400 people, 140 boats, and 5 aircraft were hired by Exxon to capture and rehabilitate oiled birds. They managed to treat 1,600 birds of 71 species, but half of them died of their injuries. The rest were treated and released to the wild, but the lingering effects of hydrocarbon poisoning likely prevented most of them from surviving for long. Even bird and mammal populations that suffered large mortality recovered to their natural abundance within a decade or less. From a strictly environmental perspective, the habitats affected by the disaster showed an impressive amount of resilience.

On the night of April 20, 2010, the Deepwater Horizon oil rig, one of hundreds operating in the Gulf of Mexico, exploded, killing eleven men, and placing one of the most rich and diverse coastal regions on earth in imminent danger of petroleum poisoning (figure 13.7.10). BP had been drilling in waters a mile deep, and in the next two days, as the rig slowly sank, it tore a gash in the pipe leading to the oil well on the ocean floor. The blowout was apparently caused by a failure of the casing of the borehole and also of the fail-safe blowout preventer. These likely occurred because of an unwise engineering decision to use an insufficient cementing regime for the borehole despite encountering extremely high geological pressure during the drilling. This resulted in a fire and explosion on the drilling platform, which sank during the fire-fighting action because of the enormous amounts of water

poured into it. The blowout lasted for 87 days and two hundred million gallons of crude oil poured into the Gulf before the technological means could be found to seal the undersea well. It was the worst environmental disaster in American history, and the largest peacetime oil spill ever.



Figure 13.7.10**:** 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).

Wildlife, ecosystems, and people's livelihood were adversely affected as crude oil spread over as much as 176-thousand km^2 of water and affected beaches from western Florida to Texas, and caused tens of billions of dollars of economic damage. A lot of money and huge amounts of energy were expended on immediate clean-up efforts. About 7,000 m^3 of dispersant was used to help protect coastal infrastructure and habitats, and also to disperse the petroleum as it issued from the subsea blowout itself. Despite the enormous effort, considerable damage was done to natural habitats, recreational beaches, the commercial fishery, and harbors. The long-term impacts are still not known. Subsequent legal actions found that British Petroleum (BP), the operator of the drilling project, bore primary responsibility for the disaster. Eventually, BP paid more than US$42-billion in criminal and civil settlements. The very fact that BP was drilling under such risky conditions—a mile underwater, in quest of oil another three miles under the ocean floor—is an expression of the global demand for oil, the world's most valuable energy resource.

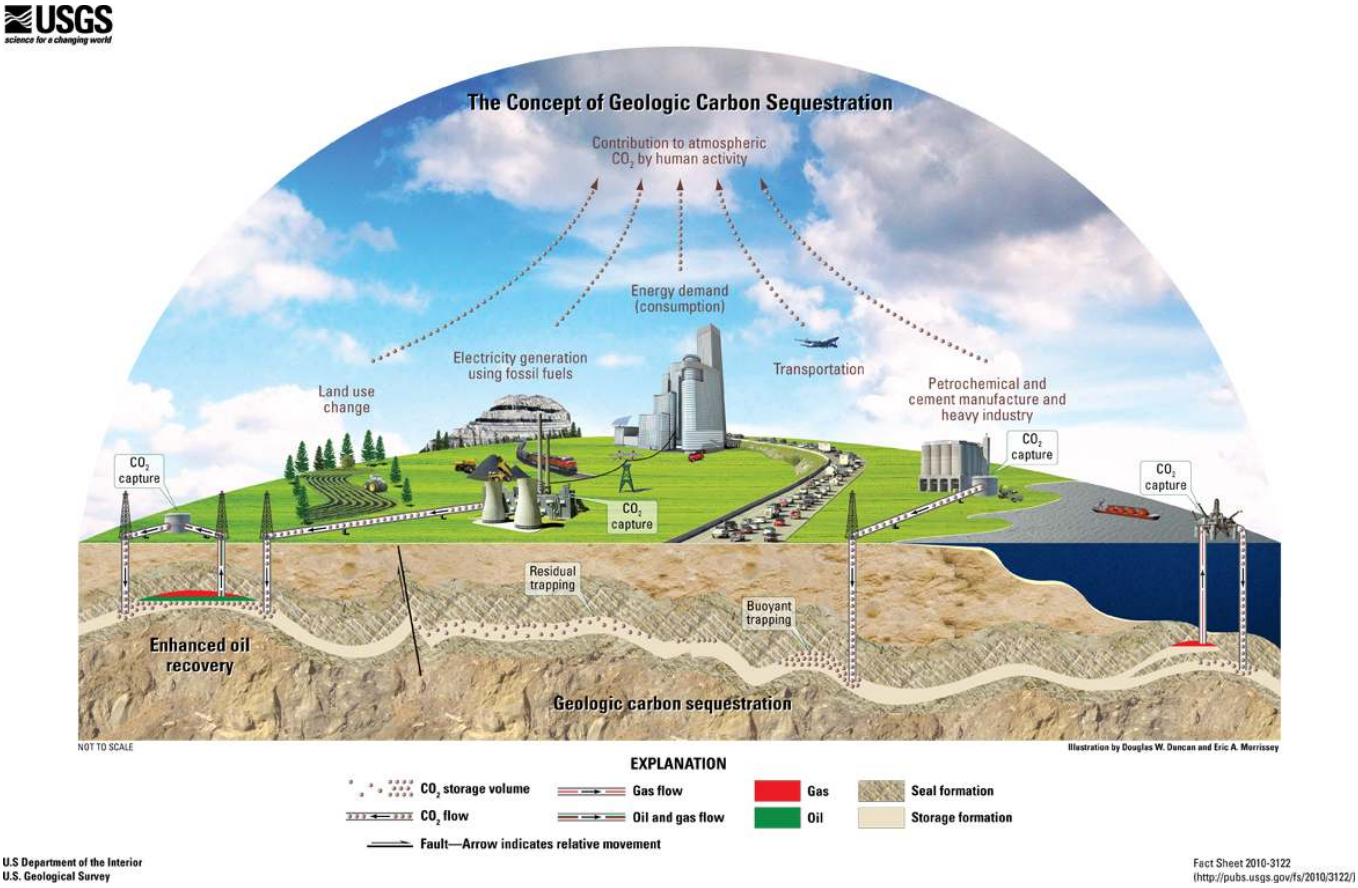
The world's largest-ever marine spill occurred during the brief Persian Gulf War of 1991. Iraqi forces deliberately released huge quantities of petroleum (about 0.8-million tonnes or approximately 200 million gallons) into the Gulf of Arabia from a Kuwaiti coastal loading facility. In part, this spill was a tactic of warfare – an attempt to make it difficult for Allied forces to execute an amphibious landing during the liberation of Kuwait. Mostly, however, the spill was an act of economic and ecological terrorism. The Iraqis also caused an enormous spillage on land during that war by igniting the more than 700 production wells in Kuwait that released enormous clouds of smoke and acid rain for over nine months.. An estimated 2-6 million tonnes of petroleum per day were emitted from the burning wells. After the Gulf War was over, it took 11 months to control and cap the blowouts. By that time, an immense 42-126-million tonnes of petroleum had spilled. Most of the crude oil burned in the atmosphere or evaporated, but 5-21 million tonnes accumulated as vast crude-oil lakes in the desert around the blowouts.

The Future of Natural Gas and Coal

The future development of coal and natural gas depend on the degree of public and regulatory concern for carbon emissions, and the relative price and supply of the two fuels. Supplies of coal are abundant in the United States, and the transportation chain from mines to power plants is well established. The primary unknown factor is the degree of public and regulatory pressure that will be placed on carbon emissions. Strong regulatory pressure on carbon emissions would favor retirement of coal and addition of natural gas power plants. This trend is reinforced by the recent dramatic expansion of shale gas reserves in the United States due to advances in drilling technology. Shale natural gas production has increased 48% annually in the years 2006 – 2010, with more

increases expected. Greater United States production of shale gas will gradually reduce imports and could eventually make the United States a net exporter of natural gas.

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 13.7.10). 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 13.7.10).



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13.8: Nuclear Energy

Nuclear Energy Consumption

The use of nuclear energy presents an interesting dilemma. On the one hand, nuclear electricity produces no carbon emissions, a major sustainable advantage in a world facing climate change. On the other hand, there is environmental risk of storing spent fuel for thousands or hundreds of thousands of years, societal risk of nuclear proliferation, and the impact of accidental releases of radiation from operating reactors. Thoughtful scientists, policy makers, and citizens must weigh these advantages and disadvantages.

Nuclear electricity came on the energy scene remarkably quickly. Following the development of nuclear technology at the end of World War II for military ends, nuclear energy quickly acquired a new peacetime path for inexpensive production of electricity. Eleven years after the end of World War II, a very short time in energy terms, the first commercial nuclear reactor produced electricity at Calder Hall in Sellafield, England. The number of nuclear reactors grew steadily to more than 400 by 1990 (figure 13.8.1), four years after the Chernobyl disaster in 1986 and eleven years following Three Mile Island in 1979 (see Consequences of Nuclear Energy). The number of operating reactors remained approximately flat for two decades, and the United States has not built a new nuclear facility since 1996. The number of operating nuclear power plants decreased in 2011, when the meltdown at the Fukushima Daiichi Nuclear Power Station caused Japan to shut down all of its nuclear power plants. Japan has since resumed use of some of its nuclear reactors.



Figure 13.8.1: Arkansas Nuclear One, a power plant in Russellville, Arkansas. Image by Edibobb (CC-BY).

World production of electricity from nuclear power was about 2795.96 terawatt-hours (TWh) in 2019, comprising 10.4% of electricity production and 4.3% of total energy consumption globally (figure 13.8.2). (For reference, the U.S. generated about 4100 TWh of electricity total in 2019.) The United States produced and consumed about 30.5% of the world's nuclear power in 2019, where nuclear power provided about 19.6% of the electricity and 8.0% of the total energy consumption (figure 13.8.3).

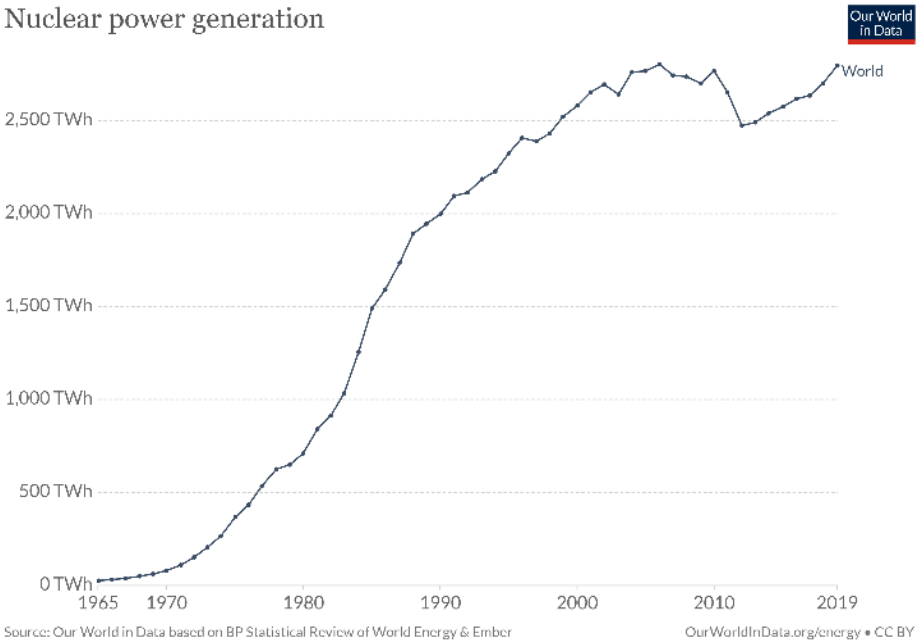


Figure 13.8.2: Global nuclear power generation in TWh over time. Nuclear power production initially increased but remained relative flat in the early 2000s. The dip in 2011 is due to the temporary shutdown of nuclear reactors in Japan following the Fukushima Daiichi Nuclear Power Station meltdown. Image from Hannah Ritchie/Our World in Data (CC-BY).

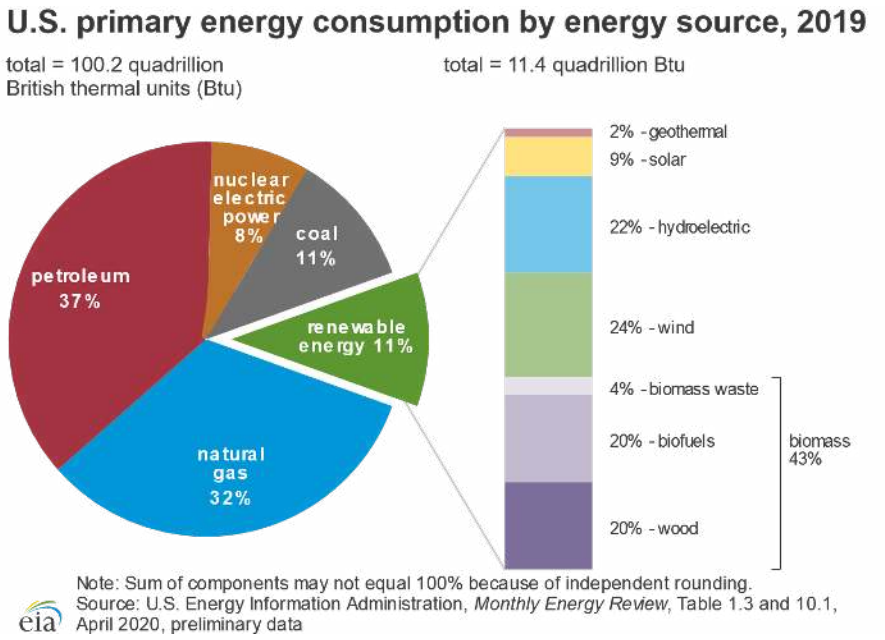


Figure 13.8.3: U.S. primary energy consumption by energy source in 2019. Nuclear power comprised 8% of total energy consumption in the U.S. Total energy consumption was 100.2 quadrillion British thermal units (Btu). Other source of energy were petroleum (37%), natural gas (32%), coal (11%), and renewable energy (11%).Total renewable energy consumption was 11.4 quadrillion Btu. This includes biomass (43%), wind (24%), hydroelectric (22%), solar (9%), and geothermal (2%). Biomass includes wood (20%), biofuels other than wood and waste (20%), and biomass waste (4%). Note: Sum of components may not equal 100% because of independent rounding. Image by EIA (public domain).

The Nuclear Fuel Cycle

Uranium ore must be mined, milled, and enriched to produce nuclear fuel. The **nuclear fuel cycle** represents the progression of nuclear fuel from creation to disposal (figure 13.8.4). The first stage of the nuclear fuel cycle is uranium recovery, in which uranium ore is **mined**. It is then milled to produce yellowcake (uranium ore concentrate/uranium oxide/U_3O_8). **Milling** separates the uranium from the other parts of the ore. Each ton of mined uranium ore typically yields 1-4 pounds of yellowcake (0.05% to 0.20% yellowcake). Next, the uranium ore concentrate is converted into uranium hexafluoride (UF_6). It is then **enriched** to increase the concentration of uranium-235 (^{235}U) relative to ^{238}U. During **fuel fabrication,** natural and enriched UF_6 is converted into into uranium dioxide (UO_2) or uranium metal alloys for use as fuel for nuclear power plants. Disposal of spent fuel rods and other hazardous waste generated in this process are discussed in Consequences of Nuclear Energy.

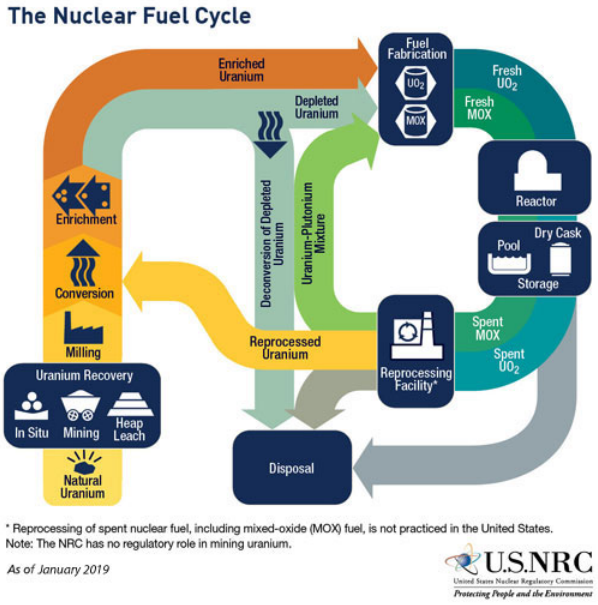


Figure 13.8.4: The nuclear fuel cycle begins with recover (mining) of natural uranium, followed by milling, conversion, and enrichment. The enriched uranium then undergoes fuel fabrication, producing uranium dioxide (UO_2) or uranium metal alloys (MOX). The fuel then goes to a nuclear reactor at the power plant. Spent fuel rods are stored in a pool or dry cask, potentially reprocessed, and sent to disposal. Reprocessed uranium can reenter earlier steps of the fuel cycle. Wastes produced during enrichment undergo deconversion before disposal. Image by U.S. NRC (public domain)

Nuclear Reactors

The fuel, which is now in the form of cylindrical ceramic pellets are then sealed into long metal tubes called **fuel rods**, which are assembled in reactor cores along with control rods. Each fuel pellet, which is about 1 cm in length, stores the same amount of energy as a ton of coal. Thousands of fuel rods form the **reactor core**, the site of nuclear fission in a nuclear power plant (figure 13.8.5).

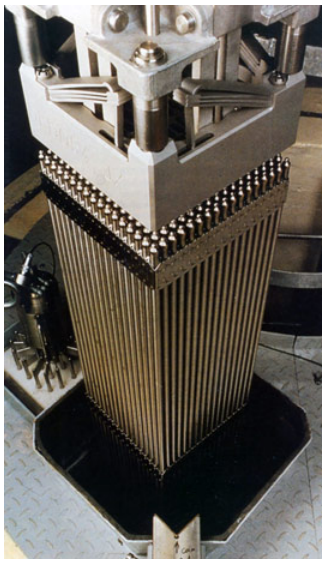


Figure 13.8.5: An assembly of fuel rods containing pellets of nuclear fuel. Image by Alternative Energies and Atomic Energy Commission, France (public domain)

Heat is produced in a nuclear reactor when neutrons strike uranium atoms, causing them to split in a continuous chain reaction that releases heat energy (figure 13.8.6). Specifically, fission of ^{235}U, releases additional neutrons, which then cause the fission of nearby ^{235}U nuclei. However, if fission occurs in too many atoms simultaneously, too much energy is released, which can cause an explosion or meltdown. This is prevented by **control rods**, which are made of a material such as boron that absorbs excess neutrons released in nuclear fission. When the neutron-absorbing control rods are pulled out of the core, more neutrons become available for fission, and the chain reaction speeds up, producing more heat. When they are inserted into the core, fewer neutrons are available for fission, and the chain reaction slows or stops, reducing the heat generated.

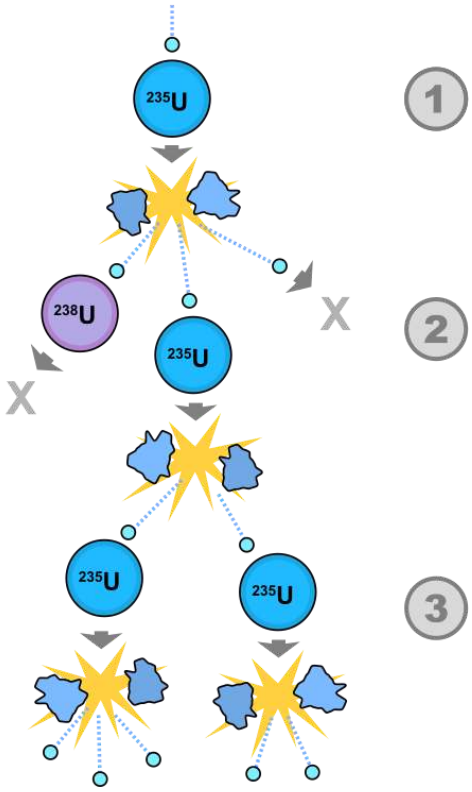


Figure 13.8.6: Schematic diagram of a fission chain reaction. (1) A uranium-235 atom absorbs a neutron, and fissions into two new atoms (fission fragments), releasing three new neutrons and energy. (2) One of those neutrons is absorbed by an atom of uranium-238, and does not continue the reaction. Another neutron is simply lost and does not collide with anything, also not continuing the reaction. However one neutron does collide with an atom of uranium-235, which then fissions and releases two neutrons and some binding energy. (3) Both of those neutrons collide with uranium-235 atoms, each of which fission and release between one and three neutrons, and so on. Image and caption (modified) by Fastfission (public domain).

Nuclear reactors (figure 13.8.7) contain the reactor core and the machinery needed to generate electricity from the heat released. The reactor core is submerged in water. In addition to transferring heat energy, the water also serves to slow down, or "moderate" the neutrons which is necessary for sustaining the fission reactions. Ultimately, the heat energy is used to generate high-pressure steam, which turns a turbine to generate electricity. The mechanism is similar to that of coal- or natural gas-generated electricity, but nuclear fission rather than combustion of coal is the source of heat energy.

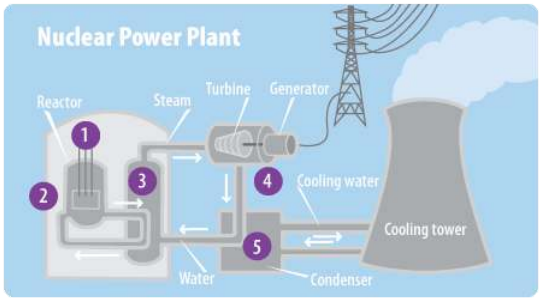


Figure 13.8.7: (1) In a nuclear reactor, fuel rods full of uranium pellets are placed in water. (2) Inside the fuel rods, uranium atoms split, releasing energy. (3) This energy heats water, creating steam. (4) The steam moves through a turbine, which turns a generator to create electricity. (5) In the condensor, the steam cools back into water, which can then be used over again. At some nuclear power plants, extra heat is released from a cooling tower. Image and caption (modified) by EPA (public domain).

There are two main types of nuclear reactors: pressurized water reactors and boiling water reactors.

Pressurized Water Reactor

In a **pressurized water reactor**, there are three separate streams of water: the water in contact with the reactor core, the water that produces steam, and the cooling water (figure 13.8.8). The reactor core is submerged in water, which is held by a steel vessel. This is surrounded by a containment structure. As the nuclear fission reaction heats the water surrounding it, the water is pumped in a cyclical stream. It transfers heat to the second stream of water, which is in a separate vessel. This second stream is kept at a lower pressure, allowing the water to boil and create steam The steam turns a turbine, generating electricity. The steam then is cooled in the **condenser** by a separate stream of cooling water. Because water from the reactor core does not mix with other parts of the reactor, not all of the reactor is radioactive.

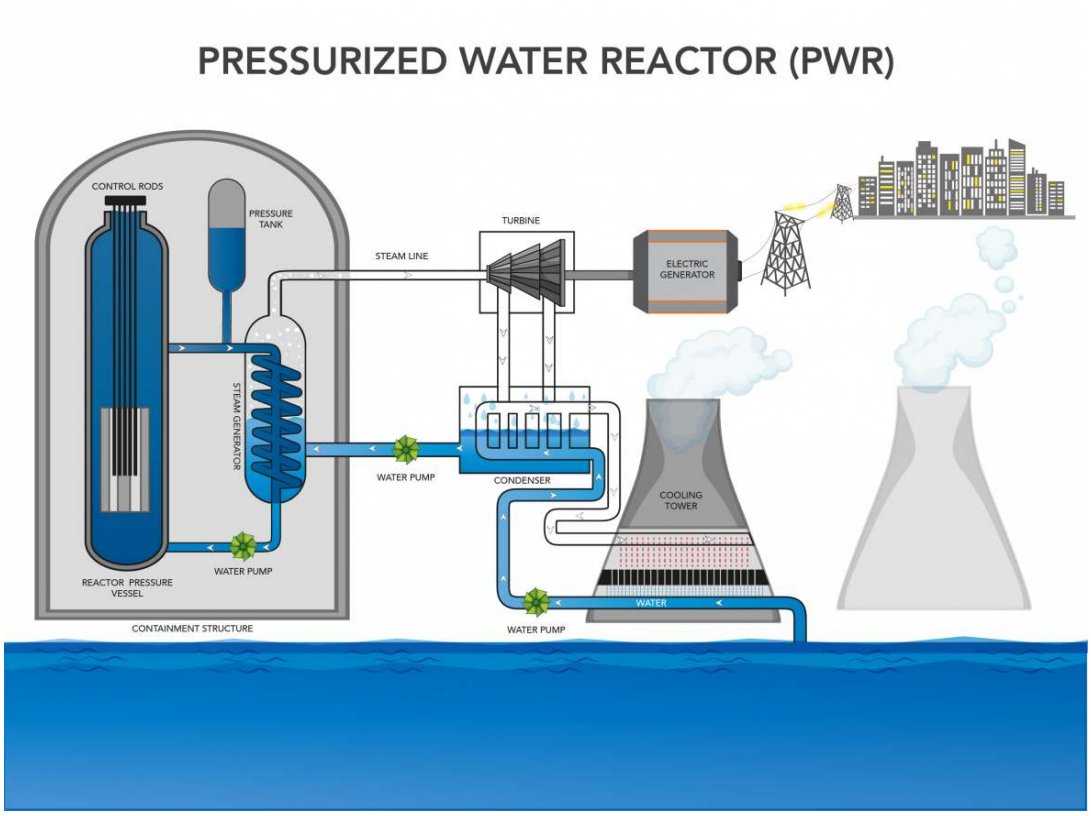


Figure 13.8.8: There are three separate streams of water in a pressurized water reactor. The first stream is associated with the reactor core in the reactor pressure vessel. The second stream is associated with the steam generator. The third stream is from an external source and is used to condense the steam. The reactor pressure vessel contains control rods and fuel rods (not labeled). The pressure tank regulates water pressure. Hot water from the reactor moves to the steam generator, where it heats water in the second stream to produce steam. Steam from the steam generator moves through the steam line and turns a turbine, powering the electric generator. Steam cools in the condenser, and the cooled water is then pumped back into the steam generator. The reactor pressure vessel, pressure tank, and steam generator are all in a containment structure. Water from an external source is used to cool steam in the condenser. The water from the external source cools in the cone-shaped cooling tower. Image by Office of Nuclear Energy/ U.S. Department of Energy (public domain).

Boiling Water Reactor

In a **boiling water reactor**, there are two separate streams of water: the water in contact with the reactor core and the cooling water (figure 13.8.9). The reactor core heats the water in which it is submerged. This water is held by a steel vessel that is surrounded by a containment structure. The steam produced as the reactor core heats water turns a turbine, which generates electricity. The steam then is cooled in the condenser by a separate stream of cooling water. Because water from the reactor core comes in contact with all parts of the reactor, the entire thing is radioactive.

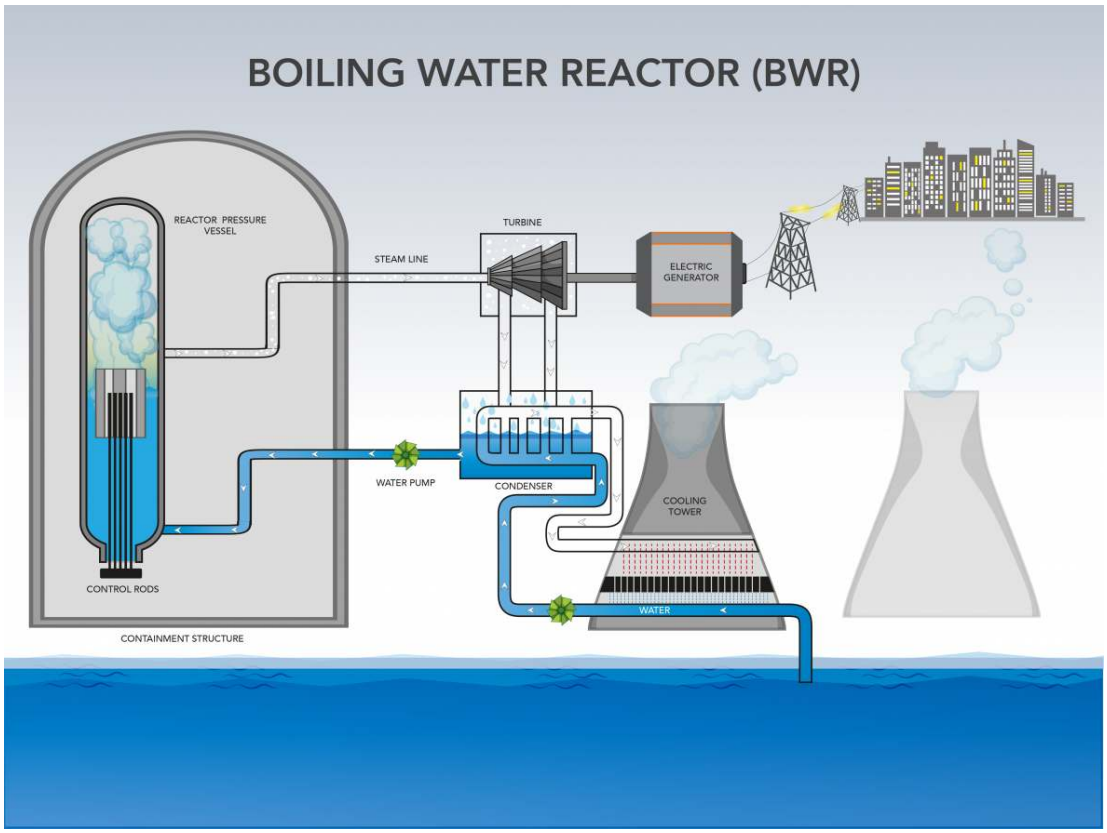


Figure 13.8.9: A boiling water reactor has two streams of water. In the first stream, the same water that bathes the reactor core in the reactor pressure vessel and turns to steam and turns a turbine. The third stream is from an external source and is used to condense the steam. The reactor pressure vessel contains control rods and fuel rods (not labeled). It is within a larger containment structure. When water is heated by the reactor, it evaporates to steam. This moves through the steam line and turns a turbine, powering the electric generator. Steam cools in the condenser, and the cooled water is then pumped back into the reactor pressure vessel. Water from an external source is used to cool steam in the condenser. The water from the external source cools in the cone-shaped cooling tower. Image by Office of Nuclear Energy/ U.S. Department of Energy (public domain).

Advantages of Nuclear Energy

In contrast to fossil fuels, generating electricity from nuclear energy does not pollute the air or significantly contribute to climate change (figure 13.8.10). As we continue to deplete global reserves of fossil fuels, supplies of nuclear fuel are abundant. It is

estimated that uranium supplies will last over 200 years, and there is potential to use other radioactive isotopes as well.

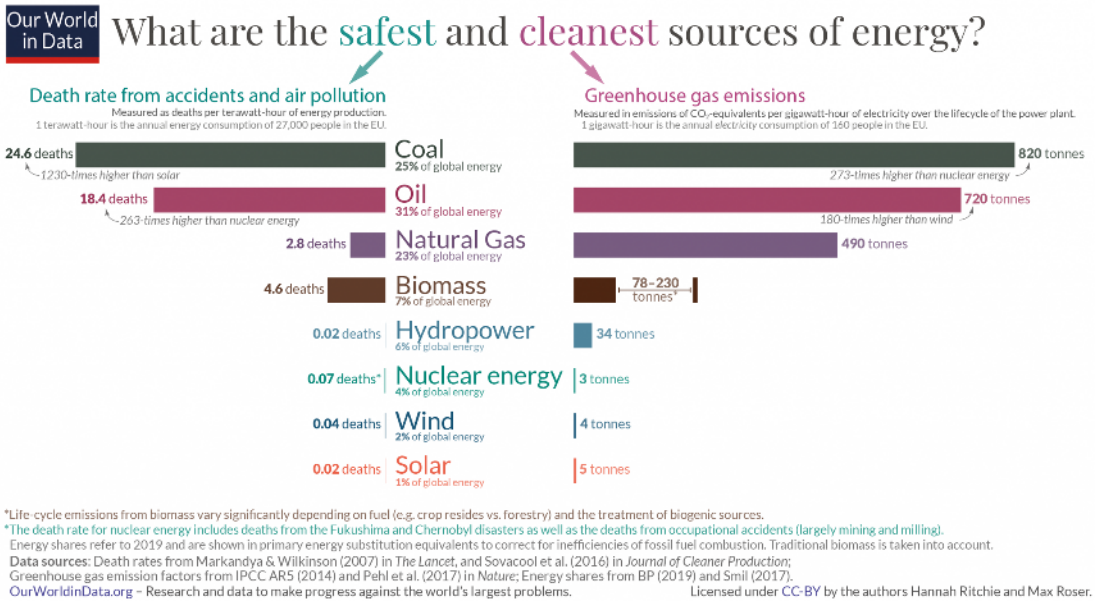


Figure 13.8.10**:** Nuclear energy causes fewer deaths and releases miniscule greenhouse gases compared to fossil fuels. These bar graphs explore the question, "What are the safest and cleanest sources of energy?". On the left is the death rate from accidents and air pollution measured as deaths per terawatt-hour (deaths/TWh) of energy production. 1 terawatt-hour is the annual energy consumption of 27,000 people in the European Union (EU). On the right are greenhouse gas emissions measured in tonnes of CO2-equivalents emitted per gigawatt-hour (tCO_2-eq/gWh) of electricity over the lifecycle of the power plant. 1 gigawatt-hour is the annual electricity consumption of 160 people in the EU. Coal accounted for 24.6 deaths/TWh, 25% of global energy, and 820 tCO_2-eq/gWh. Oil accounted for 18.4 deaths/TWh, 31% of global energy, and 720 tCO_2-eq/gWh. Coal accounted for 2.8 deaths/TWh, 23% of global energy, and 490 tCO_2-eq/gWh. Biomass accounted for 4.6 deaths/TWh, 7% of global energy, and 78-230 tCO_2-eq/gWh. Hydropower accounted for 0.02 deaths/TWh, 6% of global energy, and 34 tCO_2-eq/gWh. Nuclear energy accounted for 0.07 deaths/TWh, 4% of global energy, and 4 tCO_2-eq/gWh. Wind accounted for 0.04 deaths/TWh, 2% of global energy, and 4 tCO_2-eq/gWh. Coal accounted for 0.02 deaths/TWh, 1% of global energy, and 5 tCO_2-eq/gWh. Coal caused 1230 times more deaths than solar, and oil caused 263 times more deaths than nuclear energy. Coal emissions were 273 times higher than nuclear energy, and oil emissions were 180 times higher than wind. Image by Hannah Ritchie and Max Roser/Our World in Data (CC-BY).

Furthermore, nuclear power plants are more reliable than any other source, with a capacity factor of 93.5% (figure 13.8.11). **Capacity** is the amount of electricity a generator can produce when it's running at full blast, and the **capacity factor** is a measure of how often a plant is running at maximum power. (A power plant with a capacity factor of 100% means that it's producing power all of the time.)

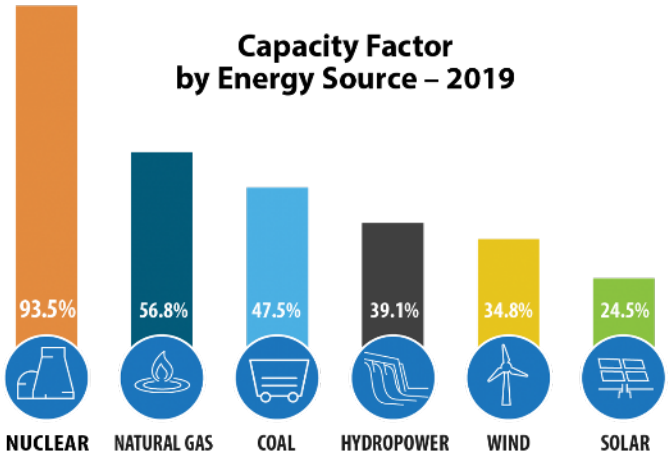


Figure 13.8.11**:** The capacity factor of six energy sources in 2019. Nuclear has the highest capacity factor at 93.5% followed by natural gas (56.8%), coal (47.5%), hydropower (39.1%), wind (34.8%), and solar (24.5%). Image from Office of Nuclear Energy/ U.S. Department of Energy (public domain).

Negative Impacts of Nuclear Energy

Despite its benefits, nuclear power has downsides. It requires more water than any other energy source. Water used for cooling is released back into the environment, and while it does not contain radioactive materials or other harmful chemicals, it is warmer than before. This is called **thermal pollution**, and it can harm aquatic life, which are adapted to cooler temperatures. Surface mining for uranium ore degrades habitat and releases toxins from underground (similar to surface mining for coal). Nuclear power plants are expensive to build and maintain, and they require large amounts of metal and concrete. Enriched uranium for nuclear fuel if in the wrong hands can be used to make nuclear weapons (figure 13.8.12). While nuclear accidents are rare, they can cause great harm, and their impacts are long-lasting. Furthermore, the problem of safely disposing spent nuclear fuel remains unresolved. The latter two concerns are discussed in more detail below.

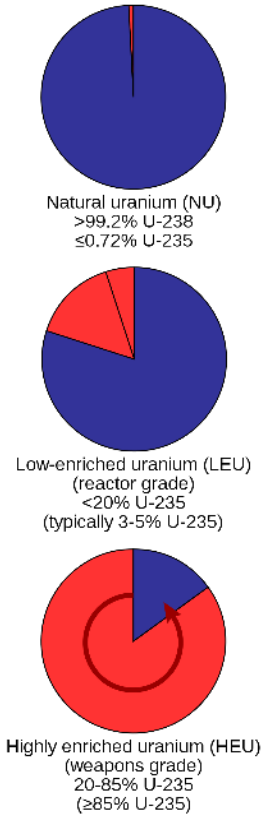


Figure 13.8.12**:** Pie charts showing the relative proportions of uranium-238 (blue) and uranium-235 (red) at different levels of enrichment. Nuclear weapons require more highly enriched uranium than is needed for nuclear fuel. Natural uranium (NU) consists of more than 99.2% U-238 and 0.72% or less of U-235. Low-enriched uranium (LEU) consists of less than 20% U-235, with reactor-grade uranium typically 2-5% U-235. High-enriched uranium (HEU) consists of 20-85% U-235 with weapons grade at least 85% U-235. Image and caption (modified) by Fastfission (public domain).

Nuclear Waste

The main environmental challenge for nuclear power is the wastes including high-level radioactive waste, low-level radioactive waste, and uranium mill tailings. These materials have long radioactive half-lives and thus remain a threat to human health for thousands of years.

High-level radioactive waste (HLRW) consists of used nuclear reactor fuel (spent nuclear fuel rods). These contain the products of nuclear fission, which are radioactive themselves. This HLRW is temporarily stored in a pool at the nuclear power plant or a dry cask, steel cylinders within another container, made of steel or concrete (figure 13.8.13). Dry casks contain inert (nonreactive) gas and may be located at the power plant, a decommissioned power plant, or a separate storage site. High-level radioactive waste may only be moved to a dry cask after one year of cooling in a pool. The U.S. has no long-term storage for HLRW, and spent fuel thus remains interim storage.

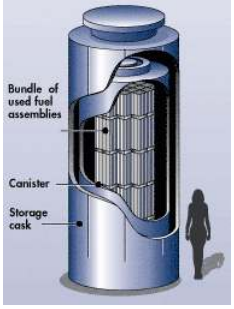


Figure 13.8.13**:** Dry casks seal spent fuel rods in a canister, which is surrounded by a larger storage cask. Bundles of used fuel assemblies are inside. Image by NRC (public domain).

Yucca Mountain in Nevada was proposed as a long-term geologic storage site, where HLRW could be buried for hundreds of thousands of years. The storage facility was constructed, but it has not been used due to opposition from local residents and concern about the safety of transporting HLNW (figure 13.8.14)



Figure 13.8.14**:** Yucca Mountain is the proposed site for long-term storage of high-level radioactive waste in the U.S., but it is not in use due to political controversy. Image by whitehouse.gov (public domain).

Some countries reprocess (recycle) spent nuclear fuel, but no recycling or reprocessing facility or a federal waste repository is currently licensed in the United States. Reprocessing separates the useable fraction of spent fuel and recycles it through the reactor, using a greater fraction of its energy content for electricity production, and sends the remaining high-level waste to permanent geologic storage.

The primary motivation for reprocessing is greater use of fuel resources, extracting about 25 percent more energy than the once through cycle. A secondary motivation for recycling is a significant reduction of the permanent geologic storage space (to 20% or less of what would otherwise be needed) and time (from hundreds of thousands of years to thousands of years). While these advantages seem natural and appealing from a sustainability perspective, they are complicated by the risk of theft of nuclear material from the reprocessing cycle for use in illicit weapons production or other non-sustainable ends. At present, France, the United Kingdom, Russia, Japan, and China engage in some form of reprocessing; the United States, Sweden, and Finland do not reprocess.

Low-level radioactive waste (LLRW) refers to items that were exposed to radiation includes clothing, filters, and gloves. These can be contained with concrete or lead (through which radiation cannot pass; figure 13.8.15).

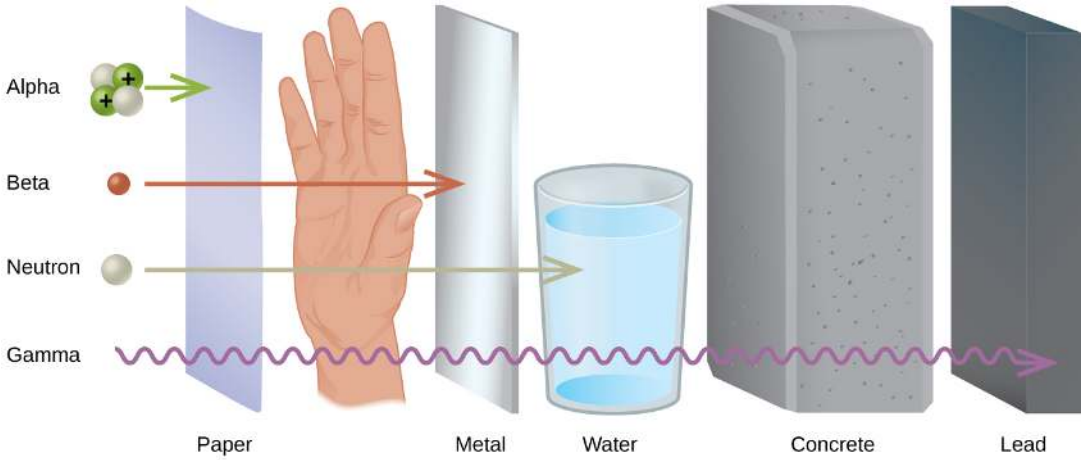


Figure 13.8.15**:** Water, thick concrete, lead, and steel (not shown) can stop several types of radiation released from radioactive wastes. Note that gamma rays can somewhat penetrate all of these substances, but lead, concrete, and steel provide a partial shield. The ability of different types of radiation to pass through material is shown. From least to most penetrating, they are alpha < beta < neutron < gamma. The top particle listed is made up of two white spheres and two green spheres that are labeled with positive signs and is labeled "Alpha." A right-facing arrow leads from this to the paper. The second particle is a red sphere labeled "Beta" and is followed by a right-facing arrow that passes through the paper and stops at the hand. The third particle is a white sphere labeled "Neutron" and is followed by a right-facing arrow that passes through the paper, hand and metal but is stopped at the glass of water. The fourth particle is shown by a squiggly arrow and it passes through all of the substances but stops at the lead. Terms at the bottom read, from left to right, "Paper," "Metal," "Water," "Concrete" and "Lead." Image and caption (modified) from Flowers, Theopold, and Langley/OpenStax (CC-BY). Download for free at CNX.

Low-level waste is typically stored at the nuclear power plant, either until it has decayed away and can be disposed of as ordinary trash, or until amounts are large enough for shipment to one of the five LLRW disposal sites in the U.S. (figure 13.8.16).

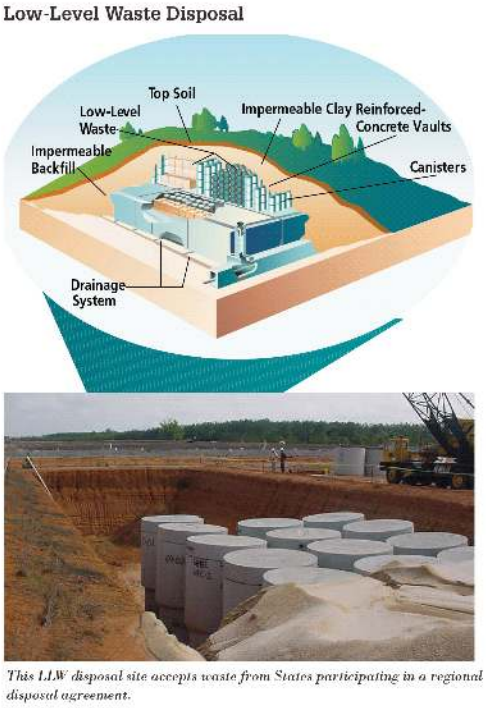


Figure 13.8.16**:** Diagram (top) and photo (bottom) of a low-level radioactive waste (LLRW or LLW) disposal site. In the diagram, low-level waste is contained in canisters within concrete vaults. This is surrounded by impermeable clay and backfill. The drainage

system prevents the wastes from contaminating groundwater. The entire disposal facility is underground, and a layer of top soil is above it. The disposal site in the photo accepts waste from States participating in a regional disposal agreement.The waste is sealed in canisters and shallowly buried. Image by NRC (public domain).

Enrichment of uranium produces depleted uranium hexafluoride (DUF_6), or **uranium mill tailings**, as a byproduct, which does not have high enough concentrations of ^{235}U to use as nuclear fuel but is still hazardous. Tailings represent the greatest percentage of nuclear waste by volume, and there are more than 200 million tons of radioactive mill-tailings in the United States. Tailings contain several radioactive elements including radium, which decays to produce radon, a radioactive gas. They are stored in **impoundments**, lined pits in the ground that are flooded with water, in remote areas. **Deconversion** involves chemically treating the tailings to reduce their hazards so that they can be stored as LLRW.

Nuclear Disasters

There are many other regulatory precautions governing permitting, construction, operation, and decommissioning of nuclear power plants due to risks from an uncontrolled nuclear reaction. The potential for contamination of air, water and food is high should an uncontrolled reaction occur. Even when planning for worst-case scenarios, there are always risks of unexpected events. The nuclear accidents at Three Mile Island, Chernobyl, and Fukushima raised concerns about the safety of nuclear power.

The Three Mile Island accident occurred in Pennsylvania in 1979. It was a partial meltdown that resulted from an electrical failure and errors in operation. There were no direct deaths. Studies investigated the possibility of exposure to radiation from the accident indirectly causing deaths through increased rates of cancer or other disease, but there has not been evidence of this. In contrast, the 1986 meltdown at Chernobyl Nuclear Power Plant in what is now the Ukraine was responsible for 50 direct deaths. This disaster occurred from a test of the emergency systems gone wrong. Estimates of indirect deaths from radiation exposure range from 4,000 to 60,000.

The global discussion regarding nuclear energy has been strongly impacted by March 2011 earthquake and subsequent tsunami that hit Japan resulted in reactor meltdowns at the Fukushima Daiichi Nuclear Power Station causing massive damage to the surrounding area. The disaster disabled the cooling system for a nuclear energy complex, ultimately causing a partial meltdown of some of the reactor cores and release of significant radiation. The design of the reactors (boiling water reactors) made it more difficult to vent the system without releasing radiation. Cooling the radioactive fuel generated a large volume of contaminated water, and the disaster costed at least $300 billion dollars. While there were no immediate deaths, one person later died from cancer attributed to radiation exposure. Thousands died as a result of stress associated with the evacuation, and about 20% of the over 160,000 evacuees had not yet returned home as of 2019.

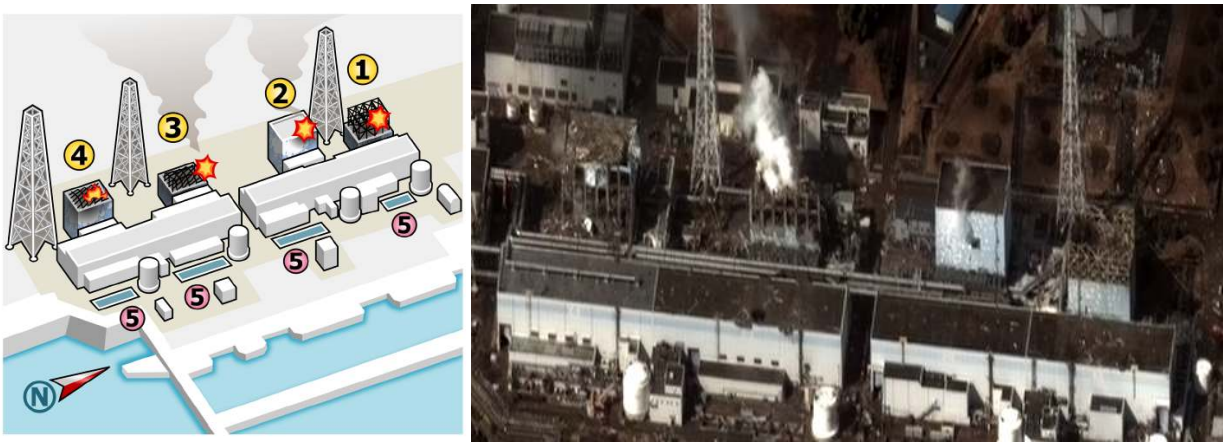


Figure 13.8.17**:** Left: Diagram (approximate) of the Fukushima I Nuclear Power plant accidents. (1) Unit 1: Explosion, roof blown off on 12 March. (2) Unit 2: Explosion on 15 March; contaminated water in underground trench, possible leak from suppression chamber. (3) Unit 3: Explosion, most of concrete building destroyed on 14 March, possible plutonium leak. (4) Fire on 15 March; water level in spent fuel pools partly restored. (5) Multiple trenches: probable source of contaminated water, partly underground, leaked stopped on 6 April. Right: The Fukushima I Nuclear Power Plant after the 2011 Tōhoku earthquake and tsunami. Reactor 1 to 4 from right to left. Left image and caption (modified) by Sodacan (CC-BY). Right image and caption by Digital Globe (CC-BY-SA).

To learn more about the Fukushima you can watch this three-minute segment, What Recovery Looks Like In Japan Almost A Decade After Fukushima Nuclear Disaster, which provides on update on evacuees from the Fukushima nuclear disaster.

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13.9: Renewable Energy Sources

Hydropower

Hydropower (hydroelectric) relies on water to spin turbines and create electricity. It is considered a clean and renewable source of energy because it does not directly produce pollutants and because the source of power is regenerated. Hydropower provides 35% of the United States' renewable energy consumption.



Figure 13.9.1. Hoover Power Plant View of Hoover Power Plant on the Colorado River as seen from above. Source: U.S. Department of the Interior

Hydropower dams and the reservoirs they create can have environmental impacts. For example, migration of fish to their upstream spawning areas can be obstructed by dams. In areas where salmon must travel upstream to spawn, such as along the Columbia River in Washington and Oregon, the dams block their way. This problem can be partially alleviated by using "fish ladders" that help salmon get around the dams. Fish traveling downstream, however, can get killed or injured as water moves through turbines in the dam. Reservoirs and operation of dams can also affect aquatic habitats due to changes in water temperatures, water depth, chemistry, flow characteristics, and sediment loads, all of which can lead to significant changes in the ecology and physical characteristics of the river both upstream and downstream. As reservoirs fill with water it may cause natural areas, farms, cities, and archeological sites to be inundated and force populations to relocate.

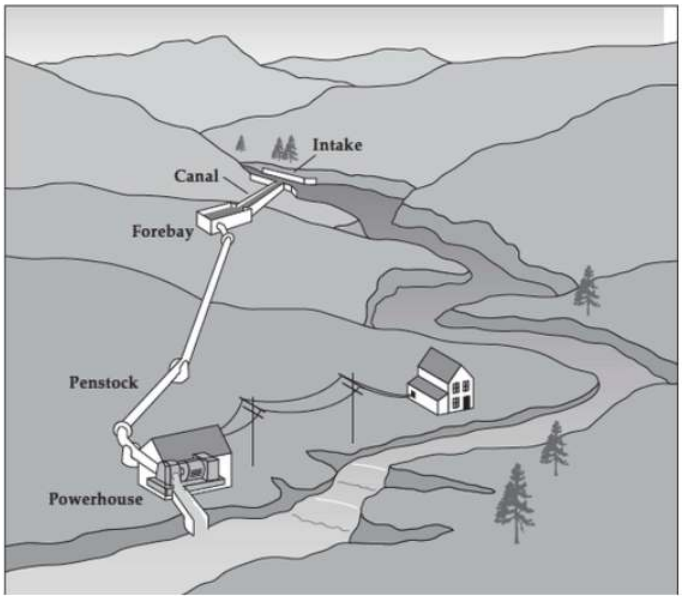


Figure 13.9.2. Microhydropower system. Although there are several ways to harness the moving water to produce energy, run-of-the-river systems, which do not require large storage reservoirs, are often used for microhydro, and sometimes for small-scale hydro, projects. For run-of-the-river hydro projects, a portion of a river's water is diverted to a channel, pipeline, or pressurized pipeline (penstock) that delivers it to a waterwheel or turbine. The moving water rotates the wheel or turbine, which spins a shaft. The motion of the shaft can be used for mechanical processes, such as pumping water, or it can be used to power an alternator or generator to generate electricity.

Large-scale dam hydropower projects are often criticized for their impacts on wildlife habitat, fish migration, and water flow and quality. However, small **run-of- the-river projects** are free from many of the environmental problems associated with their large-scale relatives because they use the natural flow of the river, and thus produce relatively little change in the stream channel and flow. The dams built for some run-of-the-river projects are very small and impound little water, and many projects do not require a dam at all. Thus, effects such as oxygen depletion, increased temperature, decreased flow, and impeded upstream migration are not problems for many run-of-the-river projects.

Small hydropower projects offer emissions-free power solutions for many remote communities throughout the world, such as those in Nepal, India, China, and Peru, as well as for highly industrialized countries like the United States. **Small hydropower systems** are those that generate between .01 to 30 MW of electricity. Hydropower systems that generate up to 100 kilowatts (kW) of electricity are often called **micro hydropower** systems (Figure 13.9.2). Most of the systems used by home and small business owners would qualify as microhydropower systems. In fact, a 10 kW system generally can provide enough power for a large home, a small resort, or a hobby farm.

Municipal Solid Waste

Municipal solid waste (MSW) is commonly known as garbage and can create electricity by burning it directly or by burning the methane produced as it decays. Waste to energy processes are gaining renewed interest as they can solve two problems at once: disposal of waste and production of energy from a renewable resource. Many of the environmental impacts are similar to those of a coal plant: air pollution, ash generation, etc. Because the fuel source is less standardized than coal and hazardous materials may be present in MSW, incinerators and waste-to-energy power plants need to clean the gases of harmful materials. The U.S. EPA regulates these plants very strictly and requires anti-pollution devices to be installed. Also, while incinerating at high temperature many of the toxic chemicals may break down into less harmful compounds. The ash from these plants may contain high concentrations of various metals that were present in the original waste. If ash is clean enough it can be "recycled" as an MSW landfill cover or to build roads, cement block and artificial reefs

Biofuel



Figure 13.9.3. Woodchips Photograph shows a pile of woodchips, which are a type of biomass. Source: Ulrichulrich

Biomass refers to material made by organisms, such as cells and tissues. In terms of energy production, biomass is almost always derived from plants, and to a lesser extent, algae. For biomass to be a sustainable option, it usually needs to come from waste material, such as lumber mill sawdust, paper mill sludge, yard waste, or oat hulls from an oatmeal processing plant, material that would otherwise just rot. Livestock manure and human waste could also be considered biomass. The use of biomass can help mitigate climate change because when burned it adds no new carbon to the atmosphere. Thinking back to the carbon cycle (chapter 3), you will recall that photosynthesis removes CO_2 through the process of carbon fixation. When biomass is burnt, CO_2 is created, but this is equal to the amount of CO_2captured during carbon fixation. Thus, biomass is a **carbon neutral** energy source because it doesn't add new CO_2 to the carbon cycle. Each type of biomass must be evaluated for its environmental and social impact in order to determine if it is really advancing sustainability and reducing environmental impacts. For example, cutting down large swaths of forests just for energy production is not a sustainable option because our energy demands are so great that we would quickly deforest the world, destroying critical habitat.

Burning Wood

Using wood, and charcoal made from wood, for heating and cooking can replace fossil fuels and may result in lower CO_2 emissions. If wood is harvested from forests or woodlots that have to be thinned or from urban trees that fall down or needed be cut down anyway, then using it for biomass does not impact those ecosystems. However, wood smoke contains harmful pollutants like carbon monoxide and particulate matter. For home heating, it is most efficient and least polluting when using a modern wood stove or fireplace insert that are designed to release small amounts of particulates. However, in places where wood and charcoal are major cooking and heating fuels such as in undeveloped countries, the wood may be harvested faster than trees can grow resulting in deforestation.

Biomass can be used in small power plants. For instance, Colgate College has had a wood-burning boiler since the mid-1980's and in one year it processed approximately 20,000 tons of locally and sustainably harvested wood chips, the equivalent of 1.17 million gallons (4.43 million liters) of fuel oil, avoiding 13,757 tons of emissions and saving the university over $1.8 million in heating costs. The University's steam-generating wood-burning facility now satisfies more than 75% of the campus's heat and domestic hot water needs.

Landfill Gas or Biogas

Landfill gas (**biogas**) is a sort of man-made "biogenic" gas as discussed above. Methane is formed as a result of biological processes in sewage treatment plants, waste landfills, anaerobic composting, and livestock manure management systems. This gas is captured and burned to produce heat or electricity. The electricity may replace electricity produced by burning fossil fuels and result in a net reduction in CO_2 emissions. The only environmental impacts are from the construction of the plant itself, similar to that of a natural gas plant.

Bioethanol and Biodiesel

Bioethanol and **biodiesel** are liquid biofuels manufactured from plants, typically crops. Bioethanol can be easily fermented from sugar cane juice, as is done in Brazil. Bioethanol can also be fermented from broken down corn starch, as is mainly done in the United States. The economic and social effects of growing plants for fuels need to be considered, since the land, fertilizers, and energy used to grow biofuel crops could be used to grow food crops instead. The competition of land for fuel vs. food can increase the price of food, which has a negative effect on society. It could also decrease the food supply increasing malnutrition and starvation globally. Also, in some parts of the world, large areas of natural vegetation and forests have been cut down to grow sugar cane for bioethanol and soybeans and palm-oil trees to make biodiesel. This is not sustainable land use. Biofuels may be derived from parts of plants not used for food, such as stalks, thus reducing that impact. Biodiesel can be made from used vegetable oil and has been produced on a very local basis. Compared to petroleum diesel, biodiesel combustion produces less sulfur oxides, particulate matter, carbon monoxide, and unburned and other hydrocarbons, but it produces more nitrogen oxide.

Liquid biofuels typically replace petroleum and are used to power vehicles. Although ethanol-gasoline mixtures burn cleaner than pure gasoline, they also are more volatile and thus have higher “evaporative emissions” from fuel tanks and dispensing equipment. These emissions contribute to the formation of harmful, ground level ozone and smog. Gasoline requires extra processing to reduce evaporative emissions before it is blended with ethanol.

Geothermal Energy

Five percent of the United States’ renewable energy comes from **geothermal energy:** using the heat of Earth’s subsurface to provide endless energy. Geothermal systems utilize a heat-exchange system that runs in the subsurface about 20 feet (5 meters) below the surface where the ground is at a constant temperature. The system uses the earth as a heat source (in the winter) or a heat sink (in the summer). This reduces the energy consumption required to generate heat from gas, steam, hot water, and conventional electric air-conditioning systems.The environmental impact of geothermal energy depends on how it is being used. Direct use and heating applications have almost no negative impact on the environment.

Geothermal power plants do not burn fuel to generate electricity so their emission levels are very low. They release less than 1% of the carbon dioxide emissions of a fossil fuel plant. Geothermal plants use scrubber systems to clean the air of hydrogen sulfide that is naturally found in the steam and hot water. They emit 97% less acid rain-causing sulfur compounds than are emitted by fossil fuel plants. After the steam and water from a geothermal reservoir have been used, they are injected back into the earth.

Solar Energy



Figure 13.9.4. Rooftop Solar Installations Rooftop solar installation on Douglas Hall at the University of Illinois at Chicago has no effect on land resources, while producing electricity with zero emissions. Source: Office of Sustainability, UIC

Solar power converts the energy of light into electrical energy and has minimal impact on the environment, depending on where it is placed. In 2009, 1% of the renewable energy generated in the United States was from solar power (1646 MW) out of the 8% of

the total electricity generation that was from renewable sources. The manufacturing of **photovoltaic** (PV) cells generates some hazardous waste from the chemicals and solvents used in processing. Often solar arrays are placed on roofs of buildings or over parking lots or integrated into construction in other ways. However, large systems may be placed on land and particularly in deserts where those fragile ecosystems could be damaged if care is not taken. Some solar thermal systems use potentially hazardous fluids (to transfer heat) that require proper handling and disposal. Concentrated solar systems may need to be cleaned regularly with water, which is also needed for cooling the turbine-generator. Using water from underground wells may affect the ecosystem in some arid locations.

Wind

Wind energy is a renewable energy source that is clean and has very few environmental challenges. Wind turbines are becoming a more prominent sight across the United States, even in regions that are considered to have less wind potential. Wind turbines (often called windmills) do not release emissions that pollute the air or water (with rare exceptions), and they do not require water for cooling. The U.S. wind industry had 40,181 MW of wind power capacity installed at the end of 2010, with 5,116 MW installed in 2010 alone, providing more than 20% of installed wind power around the globe. According to the American Wind Energy Association, over 35% of all new electrical generating capacity in the United States since 2006 was due to wind, surpassed only by natural gas.



Figure 13.9.5. Twin Groves Wind Farm, Illinois Wind power is becoming a more popular source of energy in the United States. Source: Office of Sustainability, UIC

Because a wind turbine has a small physical footprint relative to the amount of electricity it produces, many wind farms are located on crop and pasture land. They contribute to economic sustainability by providing extra income to farmers and ranchers, allowing them to stay in business and keep their property from being developed for other uses. For example, energy can be produced by installing wind turbines in the Appalachian mountains of the United States instead of engaging in mountain top removal for coal mining. Offshore wind turbines on lakes or the ocean may have smaller environmental impacts than turbines on land.

Wind turbines do have a few environmental challenges. There are aesthetic concerns to some people when they see them on the landscape. A few wind turbines have caught on fire, and some have leaked lubricating fluids, though this is relatively rare. Some people do not like the sound that wind turbine blades make. Turbines have been found to cause bird and bat deaths particularly if they are located along their migratory path. This is of particular concern if these are threatened or endangered species. There are ways to mitigate that impact and it is currently being researched. There are some small impacts from the construction of wind projects or farms, such as the construction of service roads, the production of the turbines themselves, and the concrete for the foundations. However, overall analysis has found that turbines make much more energy than the amount used to make and install them.

Interest in Renewable Energy

Strong interest in renewable energy in the modern era arose in response to the oil shocks of the 1970s, when the Organization of Petroleum Exporting Countries (OPEC) imposed oil embargos and raised prices in pursuit of geopolitical objectives. The shortages of oil, especially gasoline for transportation, and the eventual rise in the price of oil by a factor of approximately 10 from 1973 to 1981 disrupted the social and economic operation of many developed countries and emphasized their precarious dependence on

foreign energy supplies. The reaction in the United States was a shift away from oil and gas to plentiful domestic coal for electricity production and the imposition of fuel economy standards for vehicles to reduce consumption of oil for transportation. Other developed countries without large fossil reserves, such as France and Japan, chose to emphasize nuclear (France to the 80% level and Japan to 30%) or to develop domestic renewable resources such as hydropower and wind (Scandinavia), geothermal (Iceland), solar, biomass and for electricity and heat. As oil prices collapsed in the late 1980s interest in renewables, such as wind and solar that faced significant technical and cost barriers, declined in many countries, while other renewables, such as hydropower and biomass, continued to experience growth.

The increasing price and volatility of oil prices since 1998, and the increasing dependence of many developed countries on foreign oil (60% of United States and 97% of Japanese oil was imported in 2008) spurred renewed interest in renewable alternatives to ensure energy security. A new concern, not known in previous oil crises, added further motivation: our knowledge of the emission of greenhouse gases and their growing contribution to climate change. An additional economic motivation, the high cost of foreign oil payments to supplier countries (approximately $350 billion/year for the United States at 2011 prices), grew increasingly important as developed countries struggled to recover from the economic recession of 2008. These energy security, carbon emission, and climate change concerns drive significant increases in fuel economy standards, fuel switching of transportation from uncertain and volatile foreign oil to domestic electricity and biofuels, and production of electricity from low carbon sources.

Physical Origin of Renewable Energy

Although renewable energy is often classified as hydro, solar, wind, biomass, geothermal, wave and tide, all forms of renewable energy arise from only three sources: the light of the sun, the heat of the earth's crust, and the gravitational attraction of the moon and sun. Sunlight provides by far the largest contribution to renewable energy. The sun provides the heat that drives the weather, including the formation of high- and low-pressure areas in the atmosphere that make wind. The sun also generates the heat required for vaporization of ocean water that ultimately falls over land creating rivers that drive hydropower, and the sun is the energy source for photosynthesis, which creates biomass. Solar energy can be directly captured for water and space heating, for driving conventional turbines that generate electricity, and as excitation energy for electrons in semiconductors that drive photovoltaics. The sun is also responsible for the energy of fossil fuels, created from the organic remains of plants and sea organisms compressed and heated in the absence of oxygen in the earth's crust for tens to hundreds of millions of years. The time scale for fossil fuel regeneration, however, is too long to consider them renewable in human terms.

Geothermal energy originates from heat rising to the surface from earth's molten iron core created during the formation and compression of the early earth as well as from heat produced continuously by radioactive decay of uranium, thorium and potassium in the earth's crust. Tidal energy arises from the gravitational attraction of the moon and the more distant sun on the earth's oceans, combined with rotation of the earth. These three sources – sunlight, the heat trapped in earth's core and continuously generated in its crust, and gravitational force of the moon and sun on the oceans – account for all renewable energy.

Capacity and Geographical Distribution

Although renewable energies such as wind and solar have experienced strong growth in recent years, they still make up a small fraction of the world's total energy needs. The largest share comes from traditional biomass, mostly fuel wood gathered in traditional societies for household cooking and heating, often without regard for sustainable replacement. Hydropower is the next largest contributor, an established technology that experienced significant growth in the 20th Century. The other contributors are more recent and smaller in contribution: water and space heating by biomass combustion or harvesting solar and geothermal heat, biofuels derived from corn or sugar cane, and electricity generated from wind, solar and geothermal energy. Wind and solar electricity, despite their large capacity and significant recent growth, still contributed less than 1% of total energy in 2008.

The potential of renewable energy resources varies dramatically. Solar energy is by far the most plentiful, delivered to the surface of the earth at a rate of 120,000 Terawatts (TW), compared to the global human use of 15 TW. To put this in perspective, covering 100×100 km2 of desert with 10% efficient solar cells would produce 0.29 TW of power, about 12% of the global human demand for electricity. To supply all of the earth's electricity needs (2.4 TW in 2007) would require 7.5 such squares, an area about the size of Panama (0.05% of the earth's total land area). The world's conventional oil reserves are estimated at three trillion barrels, including all the oil that has already been recovered and that remain for future recovery. The solar energy equivalent of these oil reserves is delivered to the earth by the sun in 1.5 days.

The geographical distribution of useable renewable energy is quite uneven. Sunlight, often thought to be relatively evenly distributed, is concentrated in deserts where cloud cover is rare. Winds are up to 50% stronger and steadier offshore than on land. Hydroelectric potential is concentrated in mountainous regions with high rainfall and snowmelt. Biomass requires available land that does not compete with food production, and adequate sun and rain to support growth.

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13.10: 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 13.10.1). Similarly, solar tubes are lined with reflective material and can concentrate light energy to better illuminate a room (figure 13.10.1). These are embedded in the ceiling as regular light fixtures would be.



Figure 13.10.1**:** 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 13.10.2). 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.

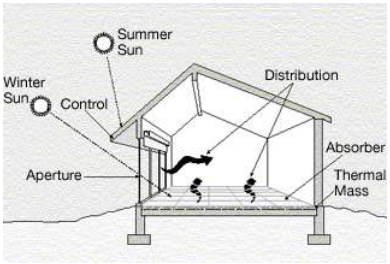


Figure 13.10.2**:** This building design uses the sun for heating during the winter and is thus a passive solar technology. The roof overhang serves as a control, blocking the higher summer sun while allowing the lower winter sunlight to pass through the window (aperture). Heat energy from the sun is 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 13.10.3). 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 13.10.3**:** 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 (figure13.10.4). This occurs in the units of the solar panel, which are called **photovoltaic cells** (PV cells; figure13.10.4 – 5). Each photovoltaic cell consists of two layers of **semiconductors**, substances that only conduct electricity under certain circumstances. (In contrast, conducts 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 13.10.4**:** 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

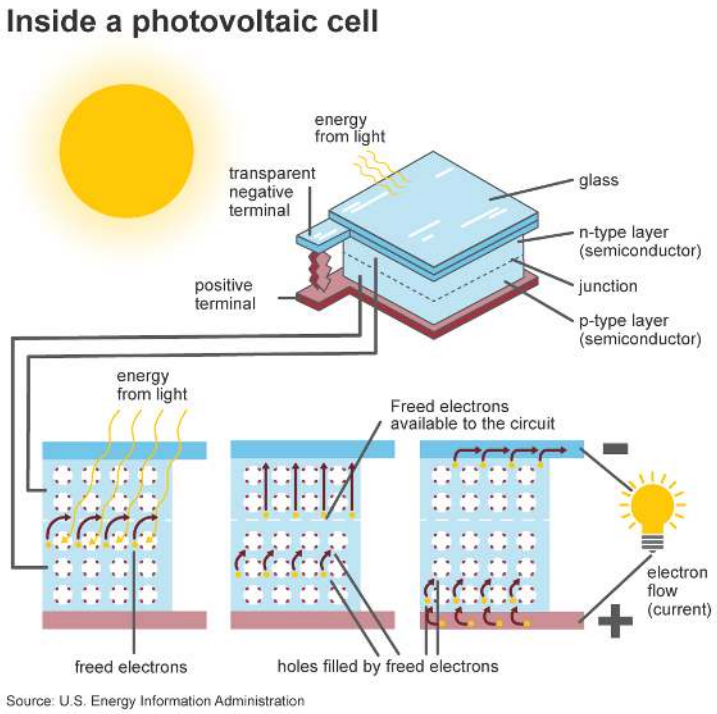


Figure 13.10.5**:** Diagram of a **photovoltaic cell** consisting of two layers of semiconductors. The top (n-type) semiconductor has extra electrons and the bottom (p-type) semiconductor has extra spots (holes) for electrons. A junction divides these two layers. Light frees the electrons and allows 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.



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 (figure13.10.6).

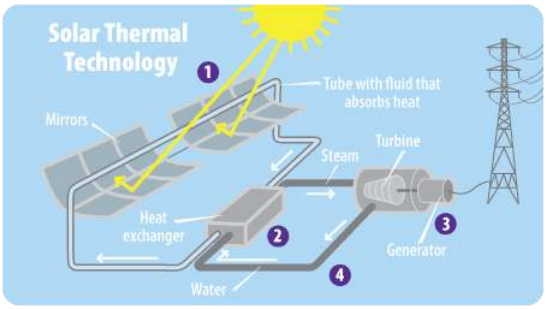


Figure 13.10.6**:** In solar thermal technology, (1) mirrors or reflectors concentrate the sun's rays to heat a special kind of liquid, which absorbs heat. (2) The heat from this liquid boils water to create steam, facilitated by the heat exchanger. (3) Steam spins a turbine that is connected to a generator, 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).

Solar energy is by far the most plentiful renewable source of energy, delivered to the surface of the earth at a rate of 120,000 Terawatts (TW), compared to the global human use of 15 TW. To put this in perspective, covering 100×100 km2 of desert with 10% efficient solar cells would produce 0.29 TW of power, about 12% of the global human demand for electricity. To supply all of the earth's electricity needs (2.4 TW in 2007) would require 7.5 such squares, an area about the size of Panama (0.05% of the earth's total land area). The world's conventional oil reserves are estimated at three trillion barrels, including all the oil that has already been recovered and that remain for future recovery. The solar energy equivalent of these oil reserves is delivered to the earth by the sun in 1.5 days.

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 geographical distribution of useable renewable solar energy is quite uneven, concentrated in deserts where cloud cover is rare. The solar resources of the United States, Germany and Spain are compared in Figure 13.10.7. The solar irradiation in the southwestern United States is exceptional, equivalent to that of Africa and Australia, which contain the best solar resources in the world. Much of the United States has solar irradiation as good or better than Spain, considered the best in Europe, and much higher than Germany.

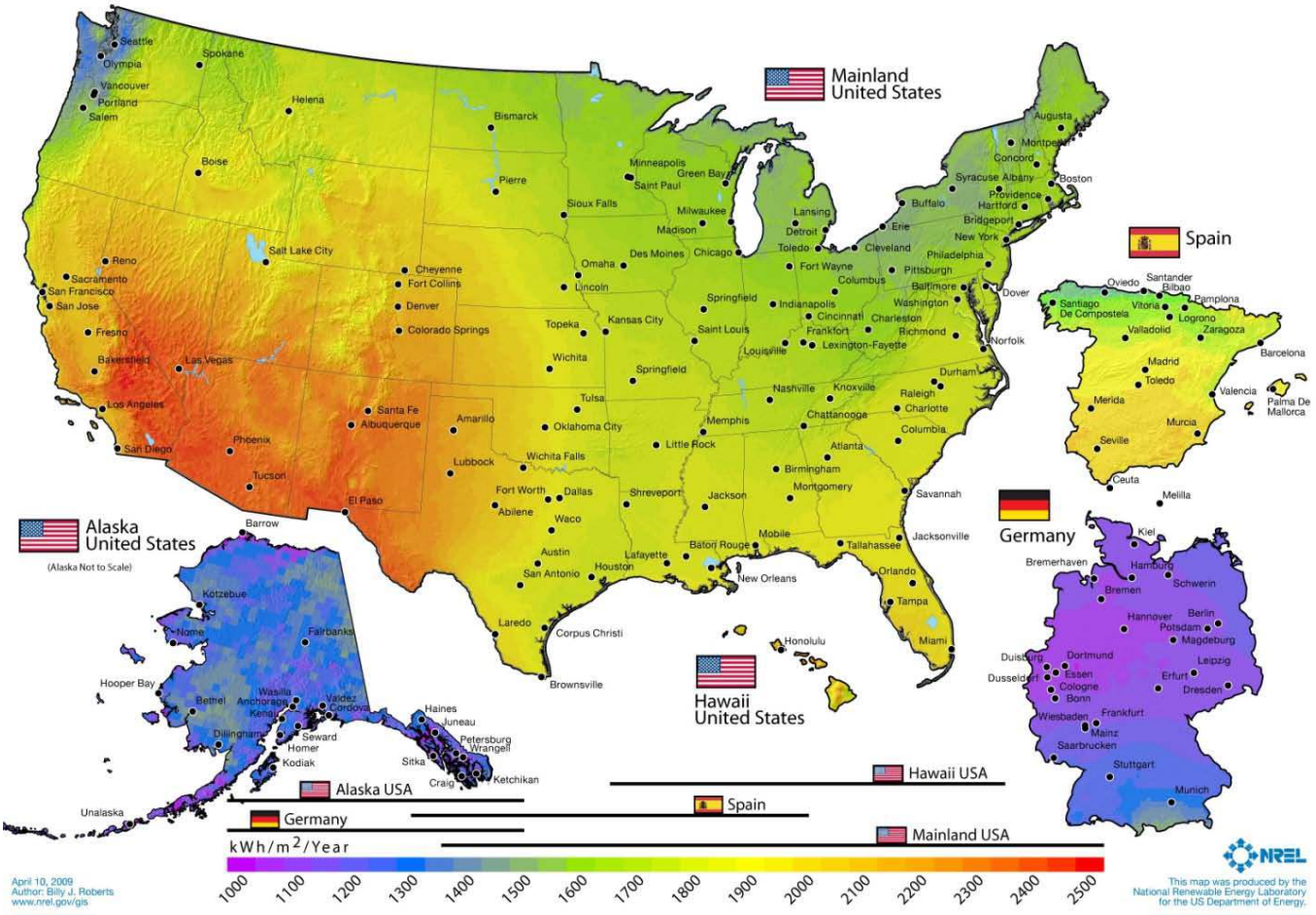


Figure 13.10.7**: Figure Solar Resources of the United States, Spain and Germany** The solar resources of the United States, Spain and Germany, expressed as solar insolation averaged over the year. The geographic variation of solar irradiation in the United States is only a factor of two, much less than for other renewable energy sources. *Source: U.S. Department of Energy, Energy Efficiency and Renewable Energy, 2008 Solar Technologies Market Report, DOE/GO-102010-2867 (January, 2010), p52.*

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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13.11: 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 13.11.1). 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.

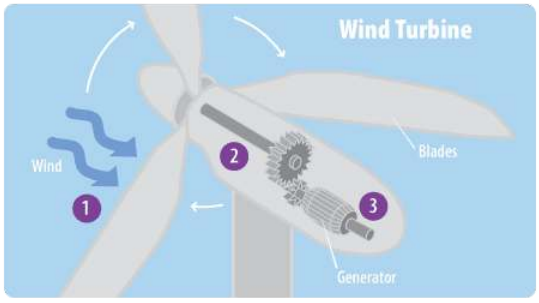


Figure 13.11.1**:** (1) As the wind blows over the blades of a wind turbine, it causes the blades to lift and rotate. (2) The rotating blades turn a shaft that is connected to a generator. (3) The generator creates electricity as it turns. Image and caption (modified) from EPA (public domain).

Advantages of Wind Energy

Wind is among the lowest-cost sources of renewable energy, and its expansion creates jobs (figure 13.11.2). 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 13.11.3).

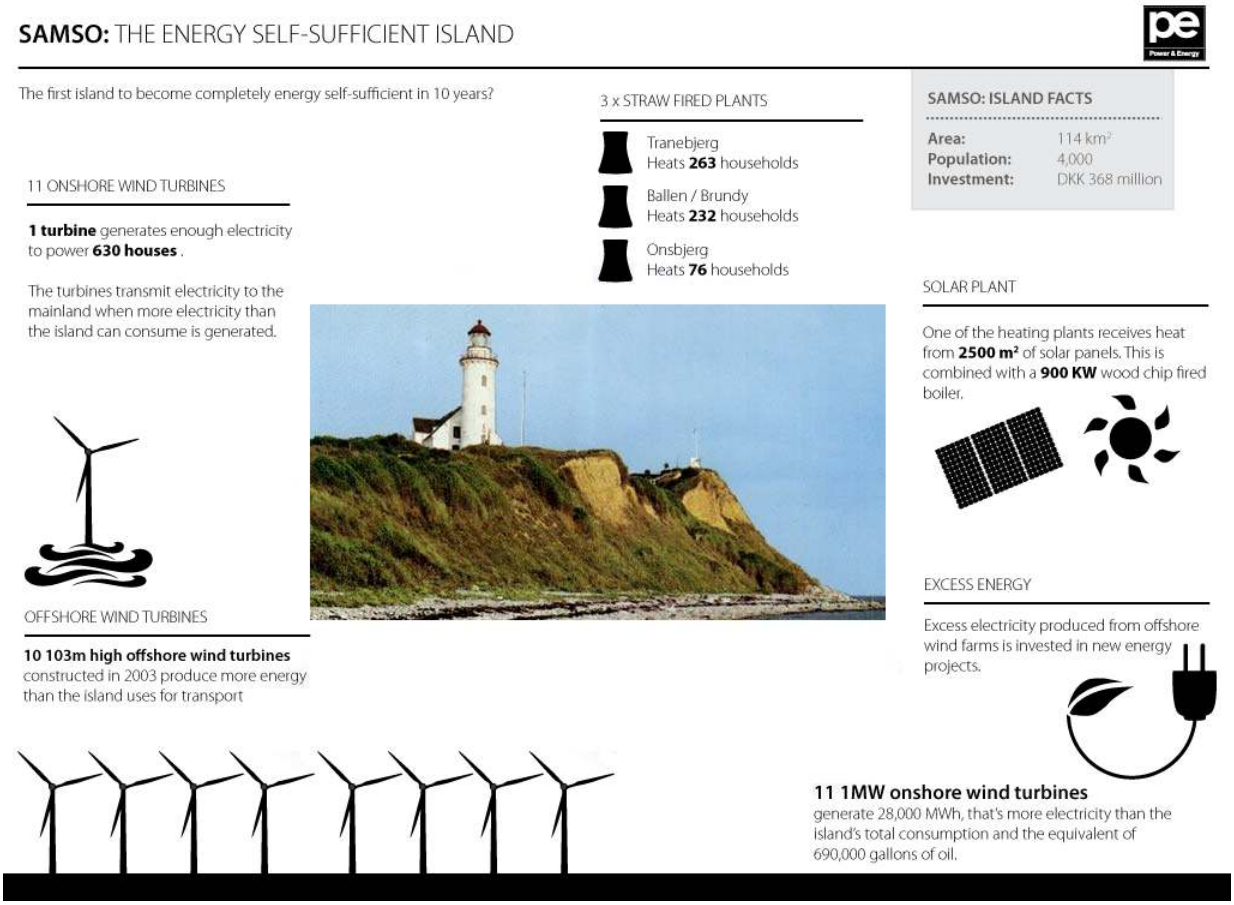


Figure 13.11.2**:** The Danish island of Samsø was the first region in the country to transition to 100% renewable energy, relying on offshore wind, onshore wind, straw (a biofuel), and solar. The text in the image is, "Samsø : The Energy Self-sufficient Island. The first island to become complete energy 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 13.11.3**:** 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.

The wind resource of the United States, while abundant, is less homogeneous. Strong winds require steady gradients of temperature and pressure to drive and sustain them, and these are frequently associated with topological features such as mountain ranges or coastlines. The onshore wind map of the United States shows this pattern, with the best wind along a north-south corridor roughly at mid-continent (Figure 13.11.4). Offshore winds over the Great Lakes and the east and west coasts are stronger and steadier though they cover smaller areas. The technical potential for onshore wind is over 8000 GW of capacity (Lu, 2009; Black & Veatch, 2007) and offshore is 800 – 3000 GW (Lu, 2009; Schwartz, Heimiller, Haymes, & Musial, 2010). For comparison, the United States used electricity in 2009 at the rate of 450 GW averaged over the day-night and summer-winter peaks and valleys.

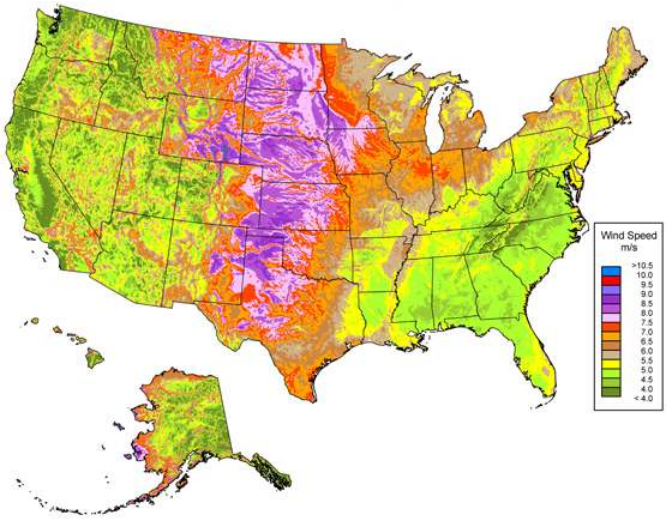


Figure 13.11.4**: 80 Meter Wind Resource Map** Figure shows the average wind speeds in the United States at 80 meters. Also see offshore wind resource maps. *Source: U.S. Department of Energy, National Renewable Energy Laboratory and AWS Truepower LLC*

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13.12: The Electrical Grid, Battery Challenges, and Energy Conservation

Electricity Grid

Over the past century and a half, **electricity** has emerged as a popular and versatile energy carrier. Today, electricity is exploited not only for its diverse end uses such as lighting, motion, refrigeration, communication, and computation, but also as a primary carrier of energy. Electricity is one of two backbones of the modern energy system (liquid transportation fuels are the other), carrying high-density energy over short and long distances for diverse uses. In 2009, electricity consumed the largest share of the United States' primary energy, 38 percent, with transportation a close second at 37 percent. These two sectors also accounted for the largest shares of U.S. carbon emissions, 38 percent for electricity and 33 percent for transportation.

By far, most electricity is generated by the combustion of fossil fuels to turn steam or gas turbines. This is the least efficient step in the energy chain, converting only 36 percent of the chemical energy in the fuel to electric energy, when averaged over the present gas and coal generation mix. It also produces all the carbon emissions of the electricity chain. Beyond production, electricity is a remarkably clean and efficient carrier. Conversion from the rotary motion of the turbine and generator to electricity, the delivery of electricity through the power grid, and the conversion to motion in motors for use in industry, transportation, and refrigeration can be more than 90 percent efficient. None of these steps produces greenhouse gas emissions. It is the post-production versatility, cleanliness, and efficiency of electricity that make it a prime energy carrier for the future. Electricity generation, based on relatively plentiful domestic coal and gas, is free of immediate fuel security concerns. The advent of electric cars promises to increase electricity demand and reduce dependency on foreign oil, while the growth of renewable wind and solar generation reduces carbon emissions. The primary sustainability challenges for electricity as an energy carrier are at the production step: efficiency and emission of carbon dioxide and toxins.

The Electricity Grid: Capacity and Reliability

Beyond production, electricity faces challenges of capacity, reliability, and implementing storage and transmission required to accommodate the remoteness and variability of renewables. The largest capacity challenges are in urban areas, where 79 percent of the United States and 50 percent of the world population live. The high population density of urban areas requires a correspondingly high energy and electric power density. In the United States, 33 percent of electric power is used in the top 22 metro areas, and electricity demand is projected to grow 31 percent by 2035. This creates an "urban power bottleneck" where underground cables become saturated, hampering economic growth and the efficiencies of scale in transportation, energy use, and greenhouse gas emissions that come with high population density. Saturation of existing cable infrastructure requires the installation of substantial new capacity, an expensive proposition for digging new underground cable tunnels.

The **reliability** of the electricity grid presents a second challenge. The United States' grid has grown continuously from its origins in the early 20th Century; much of its infrastructure is based on technology and design philosophy dating from the 1950s and 1960s, when the major challenge was extending electrification to new rural and urban areas. Outside urban areas, the grid is mainly above ground, exposing it to weather and temperature extremes that cause most power outages. The response to outages is frustratingly slow, and traditional utilities are often first alerted to outages by telephoned customer complaints, and response requires sending crews to identify and repair the damage, much the same as we did 50 years ago. The United States' grid reliability is significantly lower than for newer grids in Europe and Japan, where the typical customer experiences ten to 20 times less outage time than in the United States. Reliability is especially important in the digital age when an interruption of even a fraction of a cycle can shut down a digitally controlled data center or fabrication line, requiring hours or days to restart.

Reliability issues can be addressed by implementing a **smart grid** with two-way communication between utility companies and customers that continuously monitors power delivery, and the operational state of the delivery system, and implements demand response measures, adjusting power delivered to individual customers in accordance with a previously established unique customer protocol. Such a system requires installing digital sensors that monitor power flows in the delivery system, digital decision and control technology, and digital communication capability like that already standard for communication via the Internet. For customers with on-site solar generation capability, the smart grid would monitor and control the selling of excess power from the customer to the utility.

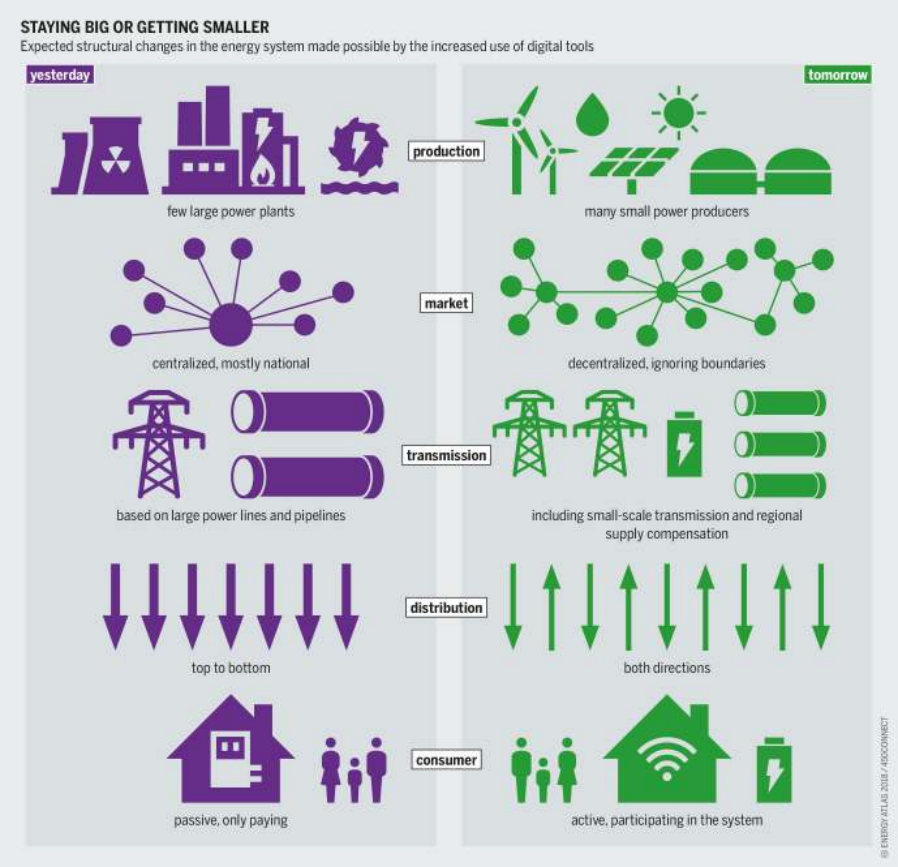


Figure 13.12.1: The electrical systems of the future will likely be made of smaller, more distributed sources and less reliance on large, centralized providers. (Bartz/Stockmar, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons)

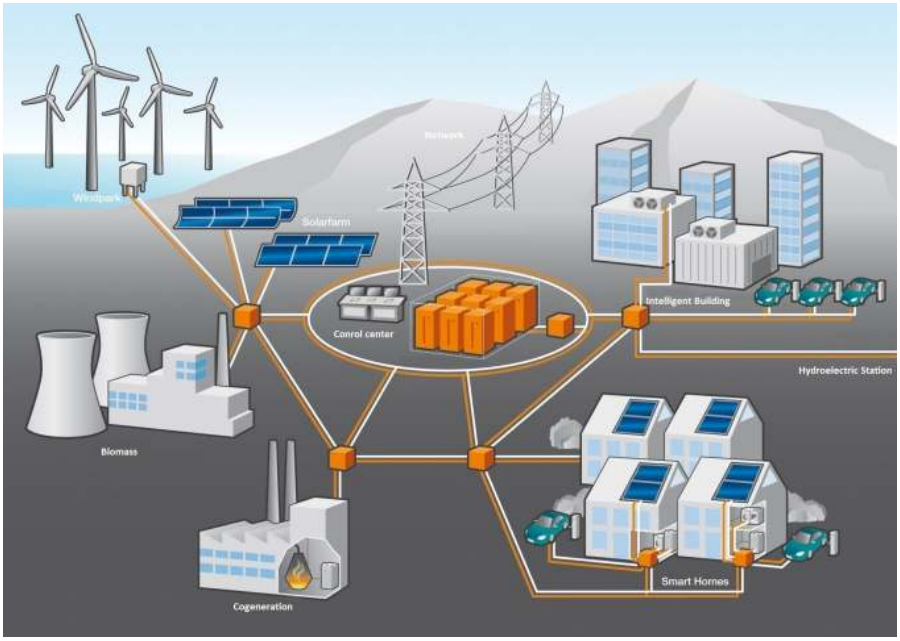


Figure 13.12.2: A smart grid plan uses the continuous flow of information in all directions to get the best balance of power sources to meet the needs of the users. Image by: Miloš Křivan, CC0, via Wikimedia Commons

The two-way communication features of the smart grid allow for the precise balancing of supply and demand information. The conventional grid in the upper panel sends power one way, from the generating station to the customer, recording how much power leaves the generator and arrives at the customer. In the smart grid, the power flow is continuously monitored, not only at the generator and the customer but also at each connection point in between. Information on the real time power flow is sent over the Internet or another special network to the utility and to the customer, allowing real-time decisions on adding generation to meet changes in load, opening circuit breakers to reroute power in case of an outage, reducing power delivered to the customer during peak periods to avoid outages (often called "demand response"), and tracking reverse power flows for customers with their own solar or other generation capacity. The conventional power grid was designed in the middle of the last century to meet the simple need of delivering power in one direction. Incorporating modern Internet-style communications and control features could bring the electricity grid to a qualitatively new level of capability and performance required to accommodate local generation and deliver higher reliability.

Smart components incorporated throughout the grid would be able to detect overload currents and open breakers to interrupt them quickly and automatically to avoid unnecessary damage and triggering a domino effect cascade of outages over wide areas as happened in the Northeast Blackout of 2003. For maximum effectiveness, such smart systems require fast automatic response on millisecond time scales commensurate with the cycle time of the grid. Even simple digital communication meets this requirement, but many of the grid components themselves cannot respond so quickly. Conventional mechanical circuit breakers, for example, take many seconds to open and much longer to close. Such long times increase the risk of dangerous overload currents damaging the grid or propagating cascades. Along with digital communications, new breaker technology, such as that based on fast, self-healing superconducting fault current limiters, is needed to bring power grid operation into the modern era.

Integrating Renewable Electricity on the Grid

Accommodating renewable electricity generation by wind and solar plants is among the most urgent challenges facing the grid. Leadership in promoting renewable electricity has moved from the federal to the state governments, many of which have legislated Renewable Portfolio Standards (RPS) that require 20 percent of state electricity generation to be renewable by 2020. 30 states and the District of Columbia have such requirements, the most aggressive being California with 33 percent renewable electricity required by 2020, and New York with 30 percent by 2015. In 2024, it is estimated that the U.S. production of renewable energy was 24% of U.S. electricity production. So, although it has taken longer than planned, significant progress has been made in the last decade.

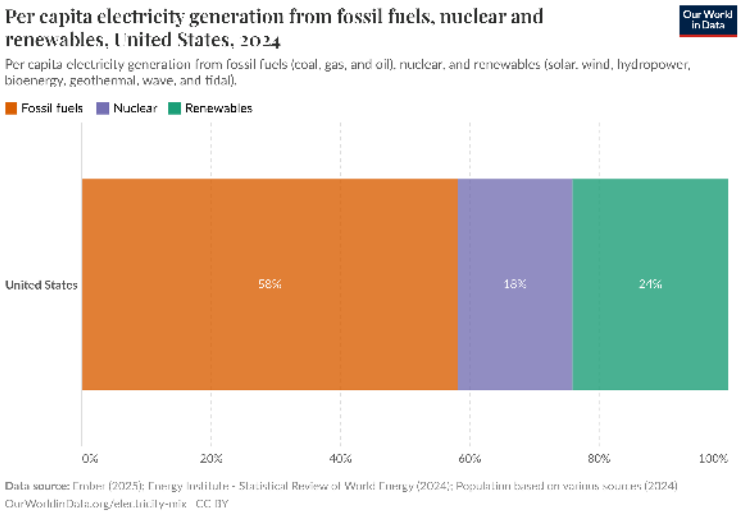


Figure 13.12.3: Per capita electricity generation from fossil fuels (coal, gas, and oil), nuclear, and renewables (solar, wind, hydropower, bioenergy, geothermal, wave, and tidal) in 2024.

Data sources: Ember (2025) Energy Institute - Statistical Review of World Energy (2024); Population based on various sources (2024) – with major processing by Our World in Data

The grid faces major challenges to accommodate the variability of wind and solar electricity. Without significant storage capacity, the grid must precisely balance generation to demand in real-time. At present, the variability of demand controls the balancing process: demand varies by as much as a factor of two from night to day as people go through their daily routines. This predictable variability is accommodated by switching reserve generation sources in and out in response to demand variations. With **renewable generation**, variation can be up to 70 percent for solar electricity due to passing clouds and 100 percent for wind due to calm days, much larger than the variability of demand. At the present level of 1.6 percent wind and solar penetration, the relatively small variation in generation can be accommodated by switching in and out conventional resources to make up for wind and solar fluctuations. At the 20 percent penetration required by state Renewable Portfolio Standards, accommodating the variation in generation requires a significant increase in the conventional reserve capacity. At high penetration levels, each addition of wind or solar capacity requires a nearly equal addition of conventional capacity to provide generation when the renewables are quiescent. This double installation to ensure reliability increases the cost of renewable electricity and reduces its effectiveness in lowering greenhouse gas emissions.

A major complication of renewable variation is its unpredictability. Unlike demand variability, which is reliably high in the afternoon and low at night, renewable generation depends on weather and does not follow any pattern. Anticipating weather-driven wind and solar generation variability requires more sophisticated forecasts with higher accuracy and greater confidence levels than are now available. Because today's forecasts often miss the actual performance target, additional conventional reserves must be held at the ready to cover the risk of inaccuracies, adding another increase to the cost of renewable electricity. Storage of renewable electricity offers a viable route to meeting the variable generation challenge.

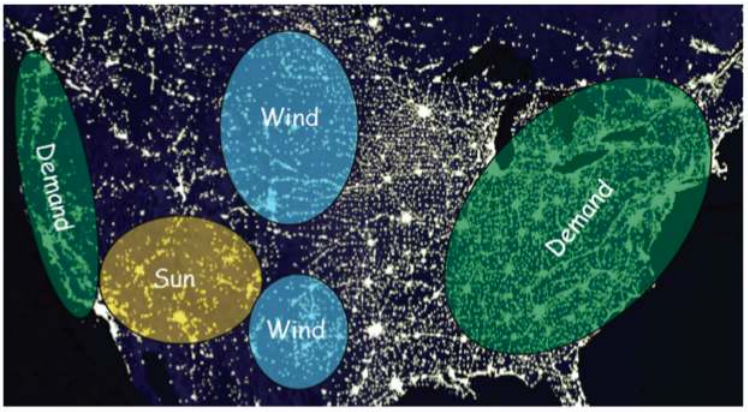


Figure 13.12.4: **Renewable Resource Location vs. Demand Location** Wind and solar electricity resources are located far from population centers, requiring a dramatic improvement in long-distance electricity transmission – an "interstate highway system for electricity." *Source:* *Integrating Renewable Electricity on the Grid, Report of the Panel on Pubic Affairs, American Physical Society (2010)*.

The final challenge for accommodating renewables is long-distance transmission. Although long-distance delivery is possible where special high-voltage transmission lines have been installed, the capacity and number of such lines are limited. The situation is much like automobile transportation before the interstate highway system was built in the 1950s. It was possible to drive coast to coast, but the driving time was long and uncertain, and the route was indirect. To use renewable electricity resources effectively, we must create a kind of interstate highway system for electricity.

Combined Heat and Power

Electricity in the United States is generated, for the most part, from central station power plants at a conversion efficiency of roughly 30 to 35 percent. Meaning that for every 100 units of fuel energy into a simple cycle central station electric power plant, we get only 30 to 35 units of electricity. The remainder of the energy in the fuel is lost to the atmosphere in the form of heat.

The thermal requirements of our buildings and facilities are generally provided **on-site** through the use of a boiler or furnace. The efficiencies of this equipment have improved over the years and now it is common to have boilers and furnaces in commercial and industrial facilities with efficiencies of 80 percent and higher. Meaning that for every 100 units of fuel energy in the boiler/furnace, we get about 80 units of useful thermal energy.

Commercial and industrial facilities that utilize the conventional energy system found in the United States (electricity supplied from the electric grid and thermal energy produced on-site through the use of a boiler/furnace) will often experience overall fuel efficiencies of between 40 to 55 percent (actual efficiency depends on the facilities heat to power ratio).

Combined Heat and Power (known also as CHP or “cogeneration”) is an integrated system located at or near the building/facility that generates utility-grade electricity which satisfies at least a portion of the electrical load of the facility, and captures and recycles the waste heat from the electric generating equipment to provide useful thermal energy to the facility.

CHP implies that heat and electricity are produced simultaneously in one process. The use of combined heat and power helps to improve the overall efficiency of electricity and heat production as these systems combine electricity production technologies with heat recovery equipment. Increasing the conversion efficiency of power generation through the use of CHP helps to reduce the environmental impact of power generation. These systems can reach fuel use efficiencies of as high as 75 to 85 percent (versus the conventional energy system at approximately 40 to 55 percent).

A well-designed, installed, and operated CHP system provides benefits for the facility owner (end user), the electric utility, and society in general. The high efficiency attained by the CHP system provides the end user with lower overall energy costs, improved electric reliability, improved electric power quality, and improved energy security. In areas where the electric utility distribution grid is in need of expansion and/or upgrades, CHP systems can provide the electric utility with a means of deferring costly modifications to the grid.

Although the electricity generated on-site by the end-user displaces the electricity purchased from the local electric utility and is seen as lost revenue by many utilities, energy efficiency and lower utility costs are in the best interest of the utility customer and should be considered as a reasonable customer option by forward-looking customer-oriented utilities. Finally, society in general benefits from the high efficiencies realized by CHP systems. The high efficiencies translate to fewer air pollutants (lower greenhouse gas and NOx emissions) than are produced from central station electric power plants.

Electricity as an Alternative Fuel Source

Electric cars represent an alternative to oil for transportation. Electric vehicles are run by an electric motor, as in a fuel cell car, up to four times as efficient as a gasoline engine. The electric motor is far simpler than a gasoline engine, having only one moving part, a shaft rotating inside a stationary housing and surrounded by a coil of copper wire. Electricity comes from a battery, whose storage capacity, like that of hydrogen materials, is too small to enable long-distance driving. Developing higher energy-density batteries for vehicles is a major challenge for the electric car industry. The battery must be charged before driving, which can be done from the grid using excess capacity available at night, or during the day from special solar charging stations that do not add additional load to the grid. Because charging typically takes hours, a potentially attractive alternative is switching the battery out in a matter of minutes for a freshly charged one at special swapping stations. A large fleet of electric cars in the United States would require significant additional electricity, as much as 130 GW if the entire passenger and light truck fleet were converted to electricity, or 30 percent of average United States electricity usage in 2008.

The energy usage of electric cars is about a factor of four less than for gasoline cars, consistent with the higher efficiency of electric motors over internal combustion engines. Although gasoline cars vary significantly in their energy efficiency, a "typical" middle-of-the-road value for a five-passenger car is 80kWh/100km. A typical electric car (such as the Think Ox from Norway, the Chevy Volt operating in its electric mode, or the Nissan Leaf) uses ~ 20 kWh/100km. While the energy cost of electric cars at the point of use is significantly less, one must consider the cost at the point of production, the electricity generating plant. If the vehicle's electricity comes from coal with a conversion efficiency of 33 percent, the primary energy cost is 60 kWh/100km, approaching but still smaller than that of the gasoline car. If electricity is generated by combined cycle natural gas turbines with 60 percent efficiency, the primary energy cost is 33 kWh/100km, less than half the primary energy cost for gasoline cars. These comparisons are presented in Table below.

Figure 13.12.5: Comparison of energy use for gasoline driven and battery driven cars, for the cases of inefficient coal generation (33%) and efficient combined cycle natural gas generation

(60%) of electricity. *Source:* George Crabtree.

	Gasoline Engine 5 passenger car	Battery Electric Nissan Leaf, Chevy Volt (battery mode), Think Ox
Energy use at point of use	80 kWh/100km	20 kWh/100km
Energy use at point of production: Coal at 33% efficiency		60 kWh/100km
Combined Cycle Natural Gas at 60% efficiency		33 kWh/100km

Comparison of carbon emissions from gasoline driven and battery driven cars, for the cases of high emission coal generation (2.1 lb CO2/kWh), lower emission natural gas (1.3 lbCO2/kWh) and very low emission nuclear, hydro, wind or solar electricity.*Source:* George Crabtree.

	Gasoline Engine 5 passenger car	Battery Electric Nissan Leaf, Chevy Volt (battery mode), Think Ox
CO2 Emissions at point of use	41 lbs	~ 0
CO2 Emissions at point of production Coal@2.1 lb CO2/kWh		42 lbs
Gas@1.3 lb CO2/kWh		25 lbs
Nuclear, hydro, wind or solar		< 1 lb

The carbon footprint of electric cars requires a similar calculation. For coal-fired electricity producing 2.1 lb CO_2/kWh, driving 100km produces 42 lbs (19 kgs) of carbon dioxide; for gas-fired electricity producing 1.3 lb CO_2/kWh, 100km of driving produces 26 lbs (11.7 kgs) of carbon dioxide. If electricity is produced by nuclear or renewable energy such as wind, solar or hydroelectric, no carbon dioxide is produced. For a "typical" gasoline car, 100km of driving produces 41 lbs (18.5 kgs) of carbon dioxide. Thus the carbon footprint of a "typical" electric car is, at worst equal, to that of a gasoline car and, at best, zero. Table Comparisons of Carbon Emissions summarizes the carbon footprint comparisons.



Figure 13.12.6: Electric cars have much better carbon emissions than their gas or diesel counterparts, even if fossil fuels are used to generate the electricity. Image from: Slowking4, GFDL 1.2 <http://www.gnu.org/licenses/old-licenses/fdl-1.2.html>, via Wikimedia Commons. https://upload.wikimedia.org/wikiped...ing_125912.jpg

Hybrid Transportation

Unlike electric cars, hybrid vehicles rely only on gasoline for their power. Hybrids do, however, have a supplemental electric motor and drive system that operates only when the gasoline engine performance is weak or needs a boost: on starting from a stop, passing, or climbing hills. Conventional gasoline cars have only a single engine that must propel the car under all conditions; it must, therefore, be sized to the largest task. Under normal driving conditions, the engine is larger and less efficient than it needs to be. The hybrid solves this dilemma by providing two drive trains, a gasoline engine for normal driving, and an electric motor for high power needs when starting, climbing hills, and passing. The engine and motor are tailored to their respective tasks, enabling each to be designed for maximum efficiency. As the electric motor is overall much more efficient, its use can raise fuel economy significantly.

The battery in hybrid cars has two functions: it drives the electric motor and also collects electrical energy from regenerative braking, converted from kinetic energy at the wheels by small generators. Regenerative braking is effective in start-stop driving, increasing efficiency up to 20 percent. Unlike gasoline engines, electric motors use no energy while standing still; hybrids therefore shut off the gasoline engine when the car comes to a stop to save the idling energy. Gasoline engines are notoriously inefficient at low speeds (hence the need for low gear ratios), so the electric motor accelerates the hybrid to ~15 mph (24 kph) before the gasoline engine restarts. Shutting the gasoline engine off while stopped increases efficiency as much as 17 percent. The energy-saving features of hybrids typically lower their energy requirements from 80 kWh/100km to 50-60 kWh/100km, a significant savings. It is important to note, however, that despite a supplementary electric motor drive system, all of a hybrid's energy comes from gasoline and none from the electricity grid.

The **plug-in hybrid** differs from conventional hybrids in tapping both gasoline and the electricity grid for its energy. Most plug-in hybrids are designed to run on electricity first and on gasoline second; the gasoline engine kicks in only when the battery runs out. The plug-in hybrid is thus an electric car with a supplemental gasoline engine, the opposite of the conventional hybrid cars described above. The value of the plug-in hybrid is that it solves the "driving range anxiety" of the consumer: there are no worries about getting home safely from a trip that turns out to be longer than expected. The disadvantage of the plug-in hybrid is the additional supplemental gasoline engine technology, which adds cost and complexity to the automobile.

The Battery Challenge

To achieve reasonable driving range, electric cars and plug-in hybrids need large batteries, one of their greatest design challenges and a potentially significant consumer barrier to widespread sales. Even with the largest practical batteries, the driving range on electricity is limited, perhaps to ~100km. Designing higher energy density batteries is currently a major focus of energy research, with advances in Li-ion battery technology expected to bring significant improvements. The second potential barrier to public acceptance of electric vehicles is charging time, up to eight hours from a standard household outlet. This may suit overnight charging at home, but could be a problem for trips beyond the battery's range – with a gasoline car, the driver simply fills up in a few minutes and is on his way. Novel infrastructure solutions such as battery swapping stations for long trips are under consideration.

From a sustainability perspective, the comparison of gasoline, electric, hybrid, and plug-in hybrid cars is interesting. Hybrid cars take all their energy from gasoline and represent the least difference from gasoline cars. Their supplementary electric drive systems reduce gasoline usage by 30-40 percent, thus promoting the conservation of a finite resource and reducing reliance on foreign oil. Electric cars, however, get all of their energy from grid electricity, a domestic energy source, completely eliminating reliance on foreign oil and use of finite oil resources. Their sustainability value is therefore higher than hybrids. Plug-in hybrids have the same potential as all-electric vehicles, provided their gasoline engines are used sparingly. In terms of carbon emissions, the sustainability value of electric vehicles depends entirely on the electricity source: neutral for coal, positive for gas and highly positive for nuclear or renewable hydro, wind, or solar. From an energy perspective, electric cars use a factor of four less energy than gasoline cars at the point of use, but this advantage is partially compromised by inefficiencies at the point of electricity generation. Even inefficient coal-fired electricity leaves an advantage for electric cars, and efficient gas-fired combined cycle electricity leaves electric cars more than a factor of two more energy efficient than gasoline cars. However, none of these comparisons take into account differences in the emissions and environmental impact of mining materials for the construction of the different types of cars and their batteries.

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 turning off and unplugging electronics when not in use, turning down the water heater, and driving efficiently. Additionally, opening blinds on south-facing windows in the morning during the winter takes advantage of passive solar technology. Relying on the sun for heating and lighting reduces the use of electricity.



Figure 13.12.7: 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 the 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 escapes in the winter or enters 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 13.12.8).



Figure 13.12.8: Energy Star appliances use energy efficiently. Image by MoneyBlogNewz (CC-BY)

This video provides a walkthrough of an energy audit.



Finally, some strategies for energy conservation require a sizeable financial investment. They can eventually pay for themselves over extended periods of time. One example is double-paned, low emissivity (low e) windows (figure 13.12.9). 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 13.12.10) are also examples of energy-conserving technologies that require sizeable investment.

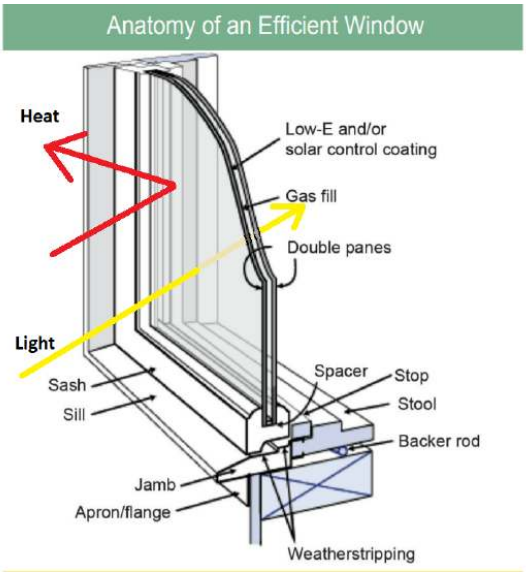


Figure 13.12.9: Anatomy of an efficient window. A double-paned, low-emissivity window allows light from the sun to pass through, but tiny metal dots (not visible) reflect heat (labeled "Low-E and/or solar control coating"). The double panes trap air between them, an insulator (labeled "gas fill"). Spacers 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 weatherstripping prevents air from leaking between the sash and the frame. The stop on the outside prevents the sash from 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).

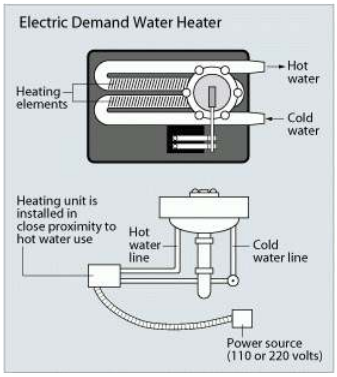


Figure 13.12.10: A tankless water heater (electric demand water heater). Because hot water is not stored, there is no opportunity for it to cool and need to be reheated. This conserves energy. The heating unit is installed in close proximity to hot water use. It is supplied by a power source (110 or 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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- Hannah Ritchie and Pablo Rosado (2020) - “Electricity Mix” Published online at OurWorldinData.org. Retrieved from: 'https://ourworldindata.org/electricity-mix' [Online Resource]. Data was last updated for 2024.
- Images added.

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13.13: 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 13.13.a). Furthermore, burning wood or straw provides heating.



Figure 13.13.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 13.13.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.

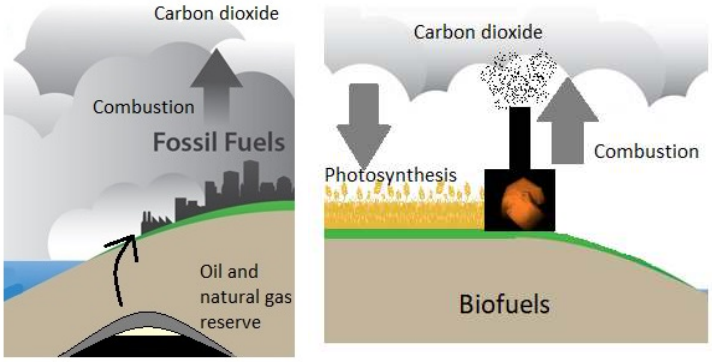


Figure 13.13.b**:** Fossil fuels, such as oil and natural gas, contain carbon that has been stored underground for millions of years. Combustion (burning) of these fossil fuels releases carbon dioxide into the atmosphere, contributing to climate change. When biofuels are grown, they capture carbon dioxide 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 13.13.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 13.13.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 13.13.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 13.13.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 13.13.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.

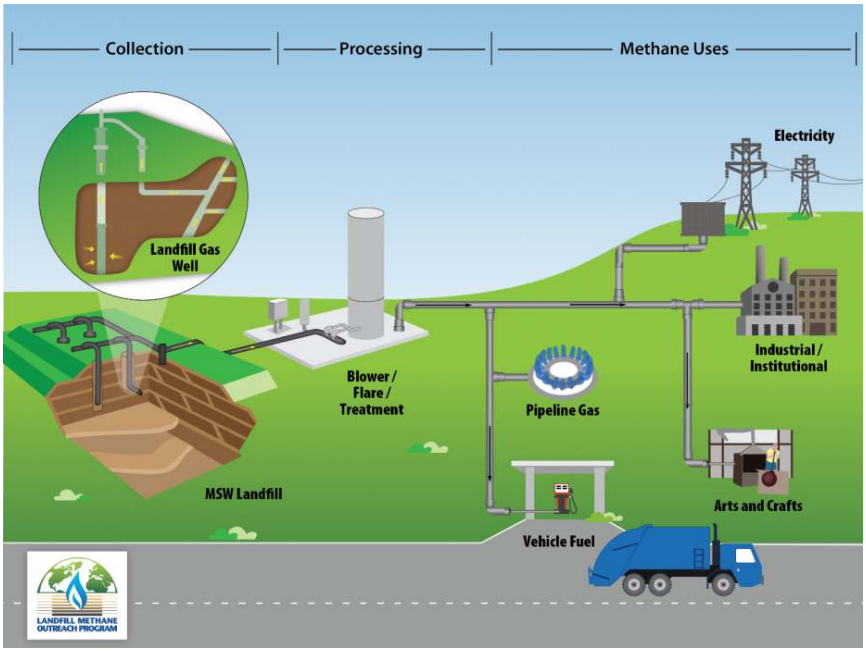


Figure 13.13.*e*: The collection and processing of landfill gas to produce methane for multiple uses. First, landfill gas is collected from the landfill gas well. A system of vertical and horizontal piping buried in an municipal solid waste landfill. The landfill gas is then processed and treated for 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 13.13.*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 13.13.f**:** A bus running on soybean biodiesel. Image and caption (modified) from U.S Department of Energy (public domain).

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13.14: 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 13.14.1) 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.

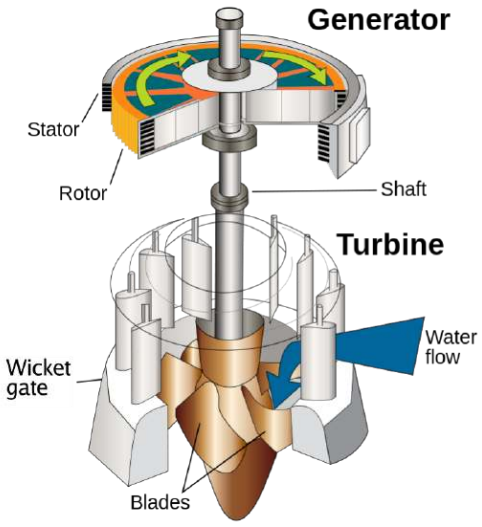


Figure 13.14.1**:** A water turbine. Moving water turns the blades of the turbine. The wicket gate controls the water flow. The moving water causes magnets in the rotor to spin and move electrons within the loops of wire in the stator, generating an electric current. Image by U.S. Army Corps of Engineers (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 13.14.2).

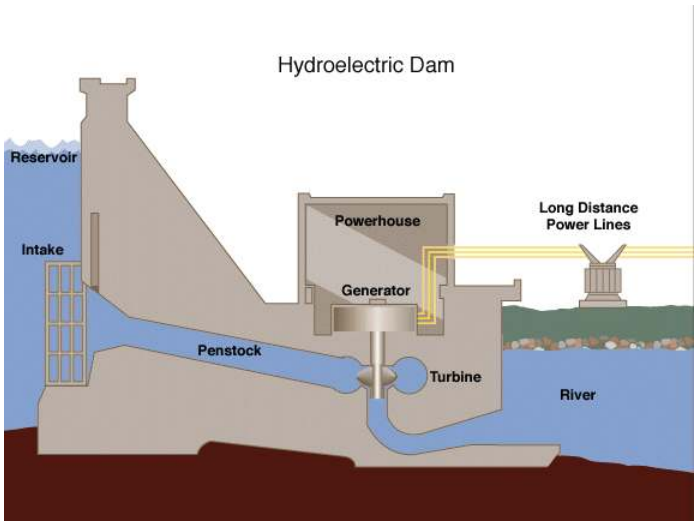


Figure 13.14.2**:** A section of a hydroelectric dam. Water in the reservoir passes through the intake into the penstock, which is a narrow channel. The moving water turns a turbine. This powers the generator in the powerhouse. The water continues down the river. Meanwhile electricity is distributed through long distance power lines. Image by Tennessee Valley Authority (public domain).

Because water is stored in a reservoir for large-scale hydropower systems with dams, these facilities have a large effect on river flow below the dam. This kind of facility has a large effect on the seasonal variation of below-dam riverflow, because it greatly reduces the spring peak flow while increasing the flow during the summer, fall, and winter (Figure 13.14.3).

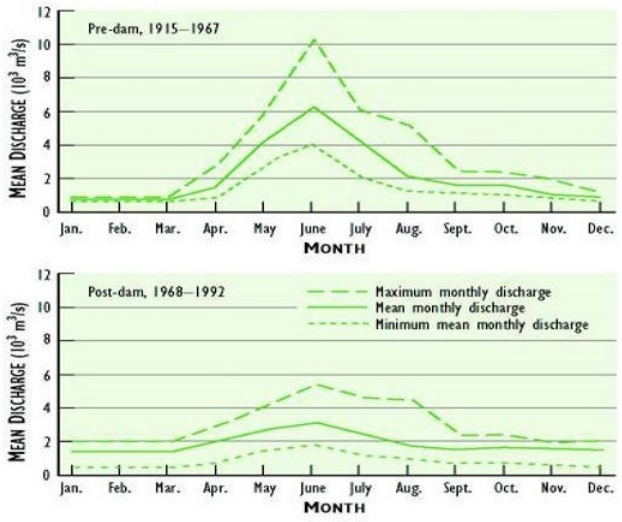


Figure 13.14.3**: Effects of Reservoir Development on Seasonal Flow of the Peace River**. The Bennett Dam and its associated reservoir were built in 1968, so the upper curves (for 1915–1967) represent pre-impoundment conditions. The flows were measured at the town of Peace River, Alberta. The most notable changes are (1) an overall reduction in the annual variation of riverflow; (2) a large reduction in peak flow during mid-April to mid-July; and (3) an increase during the low-flow period of September to March. Source: Modified from Rosenberg et al. (1997) by Bill Freedman.

In so-called peaking or **hydropeaking** systems water flow below the dam is altered throughout the day to increase flow of water (and therefore electricity generation) at times when demand for electricity is high and decrease flow of water at times when demand for electricity is lower (Figure 13.14.4). If the peak-flow system causes large flow variations downriver, important ecological damage may be caused.

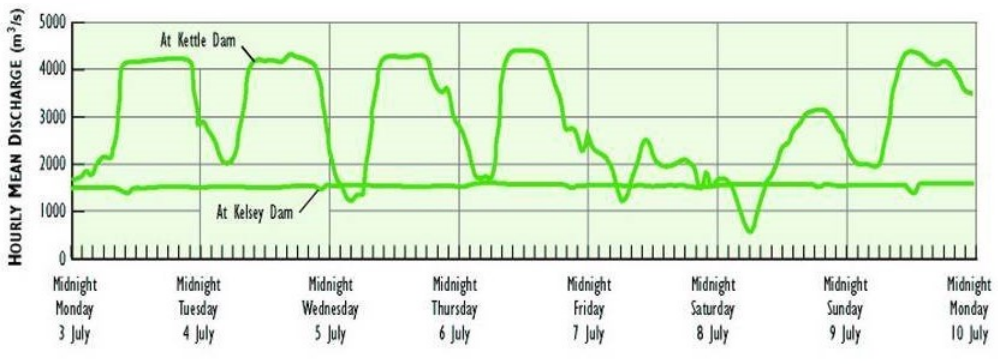


Figure 13.14.4**:** Effects of Peaking Discharges on Hourly Mean Discharge to the Nelson River. The data are for a one-week period in July 1984. This figure illustrates the changes in hydrology that occur downstream if the generation of electricity is timed to meet the peak daily demand. Note the relatively low demand during the weekend. Kelsey Dam is not subject to these peaking discharges, so it represents the background pattern of low flow in the summer. Source: Modified from Rosenberg et al. (1997) by Bill Freedman

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 13.14.5). This problem can be partially alleviated by using “fish ladders” that help salmon get around the dams (figure 13.14.6). 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.

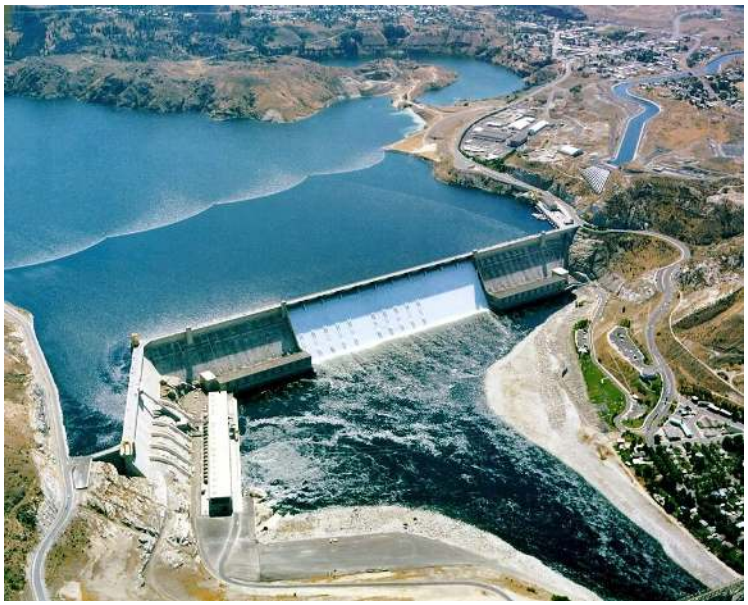


Figure 13.14.5**:** The Grand Coulee Dam on the Columbia River in Washington state created Lake Roosevelt, which provides outdoor recreation such as fishing and swimming. However, it compromised salmon populations and flooded sacred sites for people of the Spokane Tribe. Image by U.S. Bureau of Reclamation (public domain).

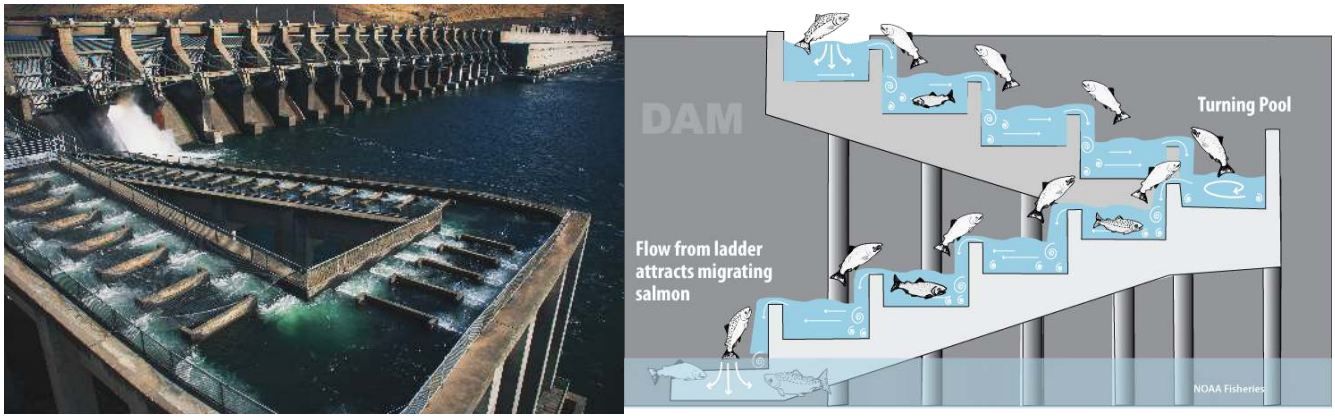


Figure 13.14.6**:** Left: The fish ladder at John Day Lock and Dam along the Columbia River in Oregon allows adult fish to migrate upstream of the dam on their own. Right: Diagram of a fish ladder, which allows the passage of salmon over a dam. Salmon swim upstream to spawn (reproduce) and are able to 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).

Large-scale dam hydropower projects are often criticized for their impacts on wildlife habitat, fish migration, and water flow and quality. However, small **run-of- the-river projects** are free from many of the environmental problems associated with their large-scale relatives because they use the natural flow of the river, and thus produce relatively little change in the stream channel and flow. 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. The dams built for some run-of-the-river projects are very small and impound little water, and many projects do not require a dam at all. Thus, effects such as oxygen depletion, increased temperature, decreased flow, and impeded upstream migration are not problems for many run-of-the-river projects.

Small hydropower projects offer 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 13.14.7). 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.

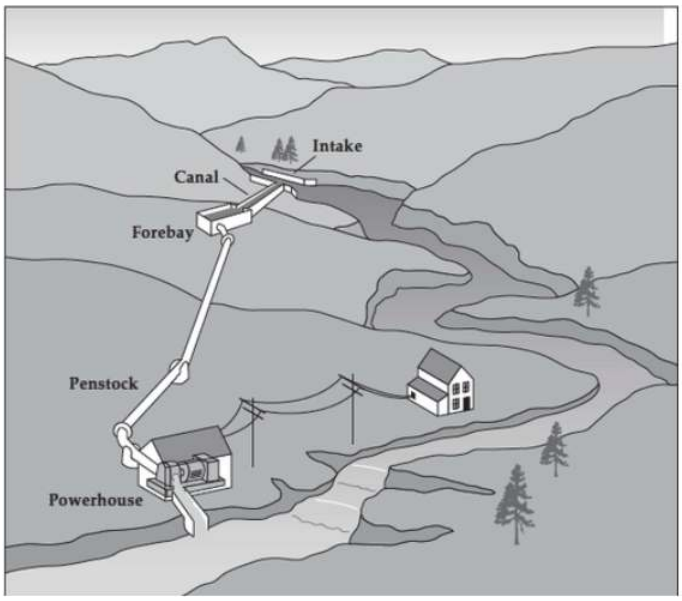


Figure 13.14.7**:** A microhydropower system. Although there are several ways to harness the moving water to produce energy, run-of-the-river systems, which do not require large storage reservoirs, are often used for microhydropower projects. For run-of-the-river hydro projects, a portion of a river's 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. 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.

Tidal energy and **energy from ocean waves** (figure 13.14.8) 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.

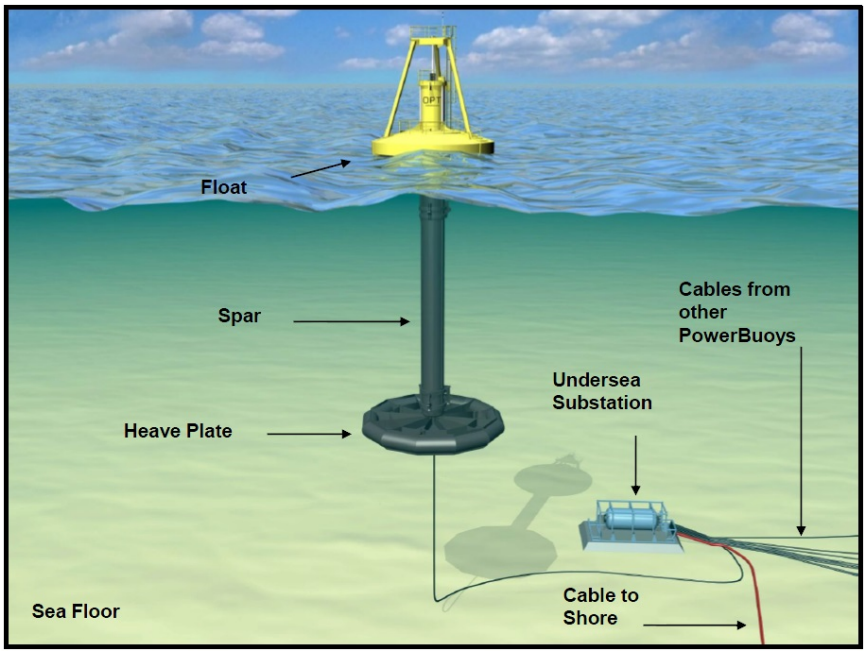


Figure 13.14.8**:** One way to harness wave energy is with an absorber. Absorbers extract energy from the rise and fall of the waves with a buoy. The buoy consists of the float, which is above the water and a heavy plate. The narrow spar connects the two. A cable connects the heavy plate of each buoy to an undersea substation, and another cable runs from the substation to the shore. Image and caption (modified) by OpenEI (public domain).

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13.15: 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 13.15.1 – 3). 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 13.15.3). Either way, the steam (or other high-pressure gas) ultimately turns a turbine and powers a generator.



Figure 13.15.1: Steam is released from a geothermal power plant. Image by Open Access Government (CC-BY).

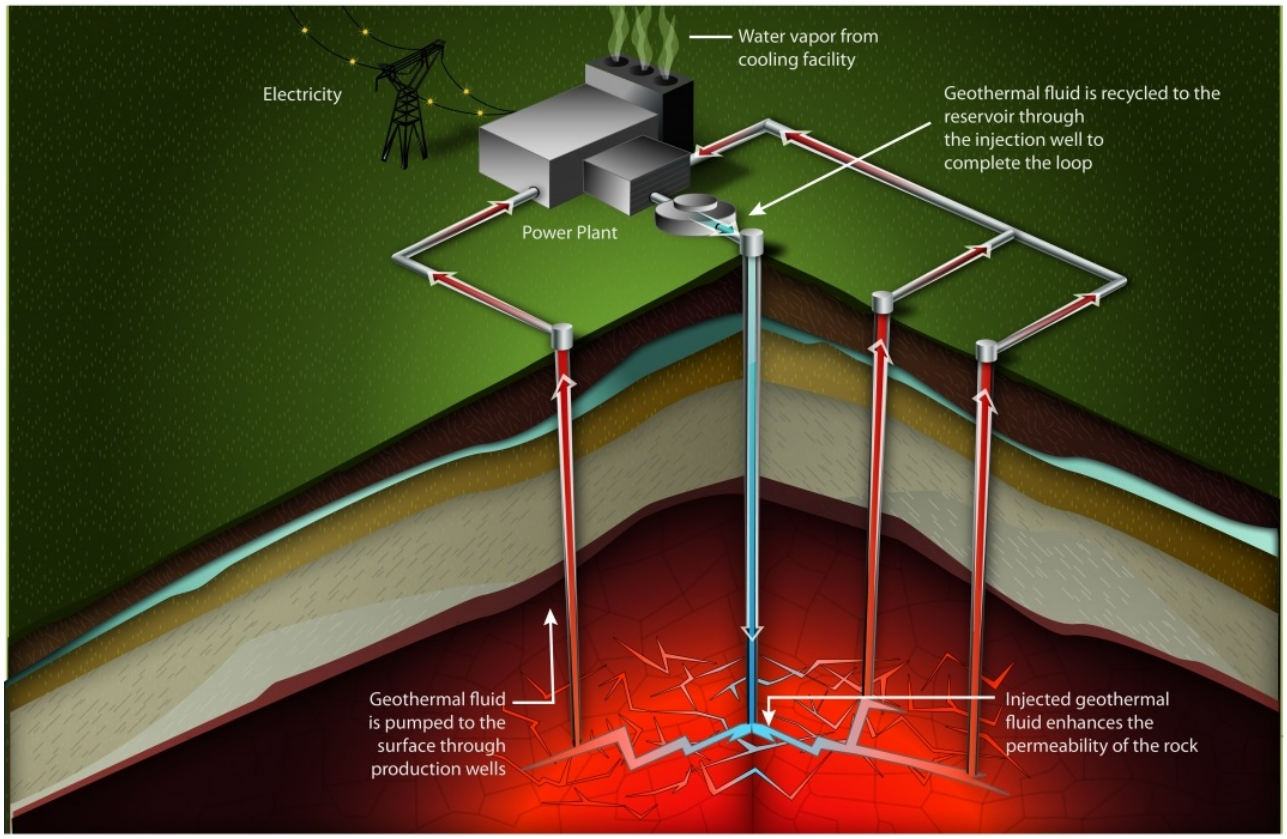


Figure 13.15.2**:** In a geothermal power plant, geothermal fluid is injected underground. (Geothermal water refers to the hot water/steam used in this process.) It enhances the permeability of the rocks and is heated underground. It exits to the surface through production wells, where it is used to 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).

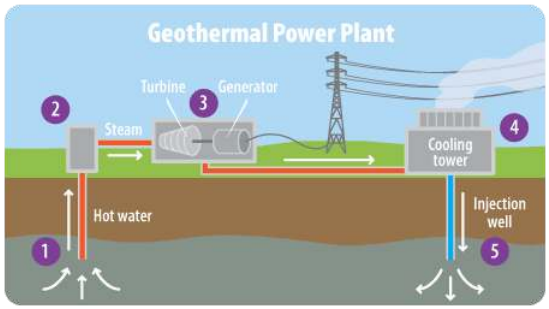


Figure 13.15.3**:** (1) In a geothermal power plant, hot water is pumped from deep underground through a well under high pressure. (2) When the water reaches the surface, the pressure is dropped, which causes the water to turn into steam. (3) The steam spins a turbine, which is connected to a generator 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 13.15.4). 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.

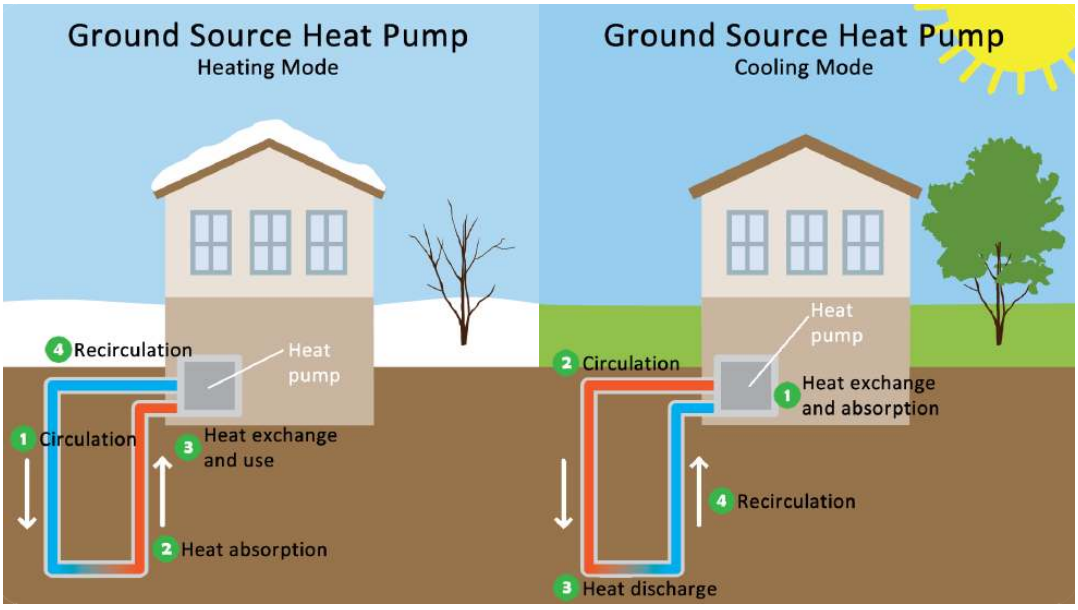
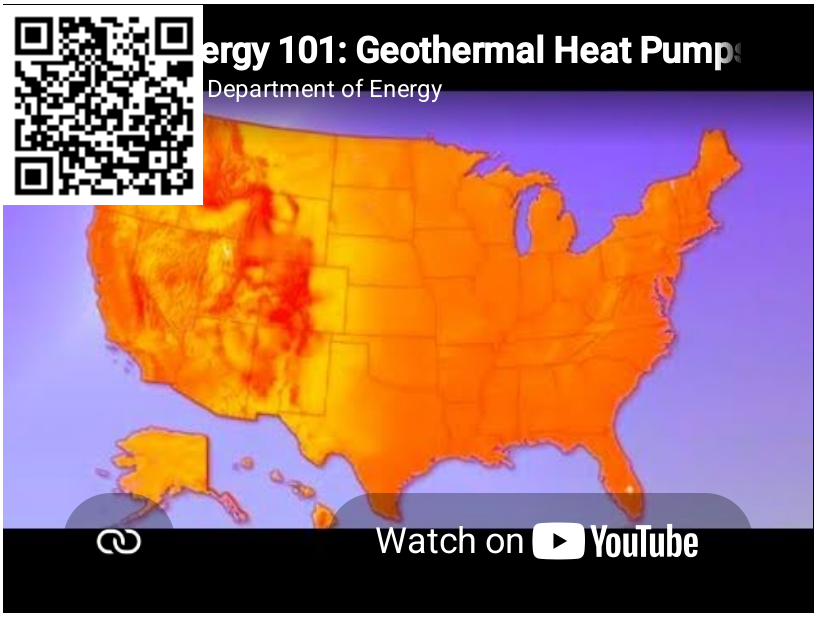


Figure 13.15.4**:** A ground source heat pump (geothermal heat pump) in heating mode (during the winter; left) and in cooling mode (during the summer; right). There are four steps for heating mode (left). (1) Circulation: The above-ground heat pump moves water or another fluid through a series of buried 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.



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 13.15.5). Additionally, geothermal power plants are costly to build.



Figure 13.15.5**:** 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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13.16: Other Alternative Renewable Energy Sources

5.7.1: Hydrogen

Hydrogen gas may be an important clean fuel of the future. Hydrogen is considered an energy carrier, like electricity and batteries, it carries energy that can be converted for use later. Hydrogen gas does not tend to exist freely but rather hydrogen atoms bind to other atoms and molecules becoming incorporated in everything from water to organic compounds. Therefore, to obtain hydrogen gas for fuel, energy is needed to force these substances to release their hydrogen atoms. One such procedure is known as **electrolysis** in which an electric current is passed through water to decompose the water molecule into oxygen and hydrogen (Figure 13.16.1). Hydrogen can also be produced from hydrocarbons such as natural gas and coal, fermentation of plant waste material, and using algae.

The nation of Iceland is attempting to become the first hydrogen-based energy economy using its abundant geothermal energy resources. Some energy experts believe that combining hydrogen fuel and electricity could serve as a basis for a clean, safe, and energy efficient energy system. Electricity generated from intermittent renewable sources such as wind and solar can be used to produce hydrogen fuel for fuel cells that would then generate electricity to power vehicles, computers, heat homes and many other uses. An energy system based on hydrogen would alleviate dependence on foreign fuels and help fight climate change. Hydrogen is the most abundant element in the universe and we will never run out of it.

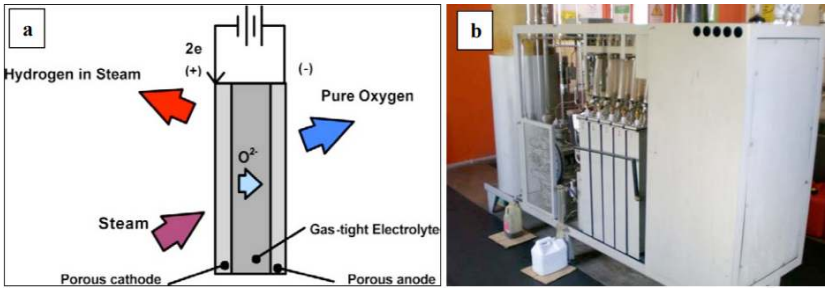


Figure 13.16.1: a) An electric current passed through water resulting in the separation of hydrogen atoms from oxygen to produce the hydrogen fuel. b) An electrolyser used in the production of hydrogen by CambridgeBayWeather. After production the hydrogen is used to inflate weather balloons to which a radiosonde is attached. The oxygen produced is vented to the outside.

Fuel Cells

Fuel cells are highly efficient power plants that produce electricity using hydrogen fuel in a chemical reaction that is a reverse of the electrolysis process that produced the hydrogen fuel (Figure 13.16.2). Energy is released by an exothermic electrochemical reaction that combines hydrogen and oxygen ions through an electrolyte material to generate electricity and heat. Experimental fuel cells that can power automobiles have been developed (Figure 13.16.2).



Figure 13.16.2: The electrochemical processes showing how hydrogen fuel is combined with oxygen generating heat energy along with water as a waste product. Some vehicles that use the fuel cell include buses (photo is a hydrogen fuel bus on Tower Bridge London, photo by Sludge G.), cars (The Toyota Fine N car based on fuel cell technology, photo by Chris 73, CC BY-SA 3.0) and motorcycles (Suzuki Burgman Fuel Cell cutaway model shown here, Photo by Mario CC BY-SA 3.0).

Challenges of Hydrogen

Currently, the infrastructure for using hydrogen fuel is lacking and converting a nation such as the United States to hydrogen would require massive and costly development of facilities to produce, store, transport, and provide the fuel. The environmental impact of hydrogen production itself depends on the source of material used to supply the hydrogen. For example, biomass and fossil fuel sources result in carbon-based emissions. Some research suggests that leakage of hydrogen from its production, transport, and use could potentially deplete stratospheric ozone. Research into this is still ongoing.

5.7.2: Electric cars

Electric cars are vehicles that solely depend on electricity to work. They are charged using fossil fuel energy sources (Figure 13.16.3 a), but they are very efficient. Although it might seem like science fiction the electric car is already here, and has been here for the last hundred years. The main problem with the electric car is that it cannot go very far before it needs to be recharged, something that takes between three to six hours. Different models have been explored (Figure 13.16.3b), but for now most cars are equipped as a hybrid with a back up reservoir using fossil fuel.

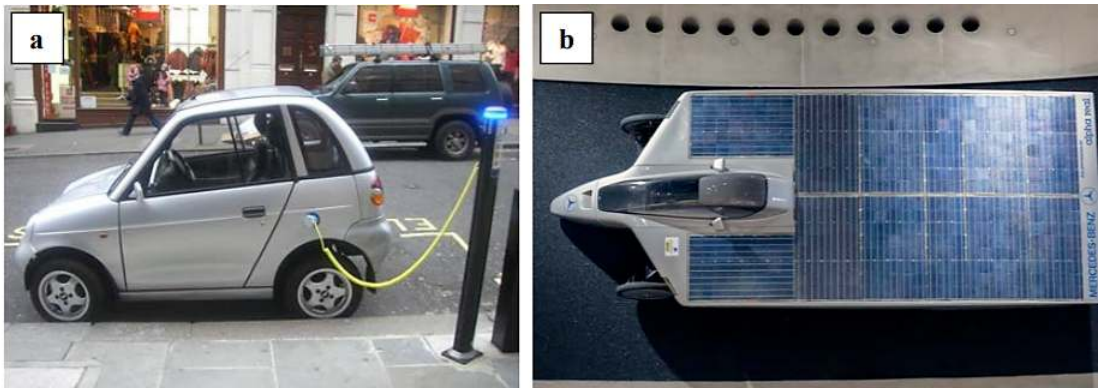


Figure 5.7.3: a) This REVAi, an electric car, gets recharged on a street in London. (credit: Frank Hebbert). b) 1985 Mercedes-Benz/Alpha Real "Tour de Sol" Solarmobile; built for the 1985 Tour de Sol Centennial Rally, solar car race from Lake Constance to Lake Geneva.

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13.17: Policy and Conservation

As we finish this chapter on energy and work, it is relevant to draw some distinctions between two sometimes misunderstood terms in the area of energy use. As has been mentioned elsewhere, the "*law of the conservation of energy*" is a very useful principle in analyzing physical processes. It is a statement that cannot be proven from basic principles, but is a very good bookkeeping device, and no exceptions have ever been found. It states that the total amount of energy in an isolated system will always remain constant. Related to this principle, but remarkably different from it, is the important philosophy of energy conservation. Conservation has to do with seeking to decrease the amount of energy used by an individual or a group through (1) reduced consumption (e.g., turning down thermostats, driving fewer kilometers) and/or (2) increasing conversion efficiencies in the performance of a particular task—such as developing and using more efficient room heaters, cars that have greater miles-per-gallon ratings, energy efficient compact fluorescent lights, energy efficient appliances, etc. Since energy in an isolated system is not destroyed or created, one might wonder why we need to be concerned about our energy resources, since energy is a conserved quantity. The problem is that the final result of most energy transformations is waste heat transfer to the environment and conversion to energy forms no longer useful for doing work. To state it in another way, the potential for energy to produce useful work has been "degraded" in the energy transformation.

A rational energy policy should encourage research by private industry and should provide funding for basic research, ensure fair access to alternative energy sources, encourage the internalization of external cost of fossil fuel energy, and promote the dissemination of information about the costs and benefits of alternative energy sources.

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13.18: Chapter Resources

Summary

We derive our energy from a multitude of resources that have varying environmental challenges related to air and water pollution, land use, carbon dioxide emissions, resource extraction and supply, as well as related safety and health issues. Each resource needs to be evaluated within the sustainability paradigm. Coal (45 percent) and gas (23 percent) are the two primary fossil fuels for electricity production in the United States. Coal combustion produces nearly twice the carbon emissions of gas combustion. Increasing public opinion and regulatory pressure to lower carbon emissions are shifting electricity generation toward gas and away from coal. Oil for transportation and electricity generation are the two biggest users of primary energy and producers of carbon emissions in the United States. Transportation is almost completely dependent on oil and internal combustion engines for its energy. The concentration of oil in a few regions of the world creates a transportation energy security issue. Nuclear electricity offers the sustainable benefit of low carbon electricity at the cost of storing spent fuel out of the environment for up to hundreds of thousands of years. Reprocessing spent fuel offers the advantages of higher energy efficiency and reduced spent fuel storage requirements with the disadvantage of higher risk of weapons proliferation through diversion of the reprocessed fuel stream.

Strong interest in renewable energy arose in the 1970s as a response to the shortage and high price of imported oil, which disrupted the orderly operation of the economies and societies of many developed countries. Today there are new motivations, including the realization that growing greenhouse gas emission accelerates global warming and threatens climate change, the growing dependence of many countries on foreign oil, and the economic drain of foreign oil payments that slow economic growth and job creation. There are three ultimate sources of all renewable and fossil energies: sunlight, the heat in the earth's core and crust, and the gravitational pull of the moon and sun on the oceans. Renewable energies are relatively recently developed and typically operate at lower efficiencies than mature fossil technologies. Like early fossil technologies, however, renewables can be expected to improve their efficiency and lower their cost over time, promoting their economic competitiveness and widespread deployment. The future deployment of renewable energies depends on many factors, including the availability of suitable land, the technological cost of conversion to electricity or other uses, the costs of competing energy technologies, and the future need for energy.

Review Questions

1. Which one of the following is not a renewable source of energy?

   A. Nuclear
   B. Wind
   C. Solar
   D. Hydropower
   E. Geothermal

2. Coal, oil, and natural gas are created _____ and contain the remains of_____.

   A. over millions of years; algae and plants
   B. over millions of years; dinosaurs and other animals
   C. over hundreds of years; algae and plants
   D. over hundreds of years; dinosaurs and other animals
   E. instantaneously; comet fragments

3. Which one of the following is a consortium of oil-producing countries that hold a significant portion of the world's oil reserves (and thus influence global oil prices)?

   A. UAE
   B. OPEC
   C. UN
   D. CITES
   E. UNESCO

4. About 44% of the electricity in the US is produced from _____. It produces about twice as much CO_2 as an equivalent amount of _____.

   A. Burning natural gas; coal

B. Hydropower; solar
C. Natural gas; Geothermal
D. Hydropower; geothermal
E. Burning coal; natural gas

5. Which one of the following is not true regarding nuclear power?
   A. Energy is captured from the radioactive decay of elements
   B. Nuclear power is considered an alternative fuel
   C. Radioactive wastes must be stored 2-5 years before disposal
   D. No CO2 is directly produced in nuclear power plants
   E. Nuclear power is used to produce electricity
6. Which one of the following directly produces CO_2 but is considered carbon neutral?
   A. Wind
   B. Biodiesel
   C. Oil
   D. Coal
   E. Hydropower
7. The original source of energy that powers both wind energy and hydropower is…
   A. Precipitation
   B. Rotation of the Earth
   C. The sun
   D. Gravity
   E. Radioactive decay within the Earth's mantle
8. Burning sawdust that is leftover from lumber production and using it to generate electricity would be an example of which one of the following?
   A. Municipal solid waste
   B. Biofuel
   C. Biogas
   D. Bioethanol
   E. Biofission
9. In the process of fracking, how is gas and oil extracted?
   A. Layers of earth are stripped away from the surface, exposing the fossil fuels
   B. Mining tunnels are created and the fossil fuels are extracted by teams working below ground
   C. Ocean sediments are mined and the fossil fuels are chemically extracted
   D. High-pressure fluids are injected underground to force out the fossil fuels
   E. Offshore drilling pads tap into pre-existing cracks in the Earth's crust
10. What fundamental similarity is shared between the following energy sources: biogas and municipal solid waste?
    A. Both burn waste to generate CO2, which itself is burned to create electricity
    B. Both chemically transform waste into oil
    C. Both trap the heat generated from decaying waste and use it to generate energy
    D. Both rely on the generation and combustion of methane
    E. Both produce no CO_2

See Appendix for answers

Attributions

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CHAPTER OVERVIEW

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14.1: Environmental Concerns with Wastes

Managing Growing Waste Generation

An enormous quantity of wastes are generated and disposed of annually. Alarmingly, this quantity continues to increase on an annual basis. Industries generate and dispose over 7.6 billion tons of industrial solid wastes each year, and it is estimated that over 40 million tons of this waste is hazardous. Nuclear wastes as well as medical wastes are also increasing in quantity every year.

Generally speaking, developed nations generate more waste than developing nations due to higher rates of consumption. Not surprisingly, the United States generates more waste per capita than any other country. High waste per capita rates are also very common throughout Europe and developed nations in Asia and Oceania. In the United States, about 243 million tons (243 trillion kg) of MSW is generated per year, which is equal to about 4.3 pounds (1.95 kg) of waste per person per day. Nearly 34 percent of MSW is recovered and recycled or composted, approximately 12 percent is burned a combustion facilities, and the remaining 54 percent is disposed of in landfills. Waste stream percentages also vary widely by region. As an example, San Francisco, California captures and recycles nearly 75 percent of its waste material, whereas Houston, Texas recycles less than three percent.

With respect to waste mitigation options, landfilling is quickly evolving into a less desirable or feasible option. Landfill capacity in the United States has been declining primarily due to (a) older existing landfills that are increasingly reaching their authorized capacity, (b) the promulgation of stricter environmental regulations has made the permitting and siting of new landfills increasingly difficult, (c) public opposition (e.g. "Not In My Backyard" or NIMBYism) delays or, in many cases, prevents the approval of new landfills or expansion of existing facilities.



Solid waste has been bought by the inhabitants of Petite Anse (Cap-Haitien, Haiti) to create a road and "soil", after it has decomposed. Rémi Kaupp, CC BY-SA 3.0 <http://creativecommons.org/licenses/by-sa/3.0/>, via Wikimedia Commons

Effects of Improper Waste Disposal and Unauthorized Releases

Prior to the passage of environmental regulations, wastes were disposed improperly without due consideration of potential effects on the public health and the environment. This practice has led to numerous contaminated sites where soils and groundwater have been contaminated and pose risk to the public safety. Of more than 36,000 environmentally impacted candidate sites, there are more than 1,400 sites listed under the Superfund program National Priority List (NPL) which require immediate cleanup resulting from acute, imminent threats to environmental and human health. The USEPA identified about 2,500 additional contaminated sites

that eventually require remediation. The United States Department of Defense maintains 19,000 sites, many of which have been extensively contaminated from a variety of uses and disposal practices. Further, approximately 400,000 underground storage tanks have been confirmed or are suspected to be leaking, contaminating underlying soils and groundwater. Over $10 billion (more than $25 billion in current dollars) were specifically allocated by CERCLA and subsequent amendments to mitigate impacted sites. However, the USEPA has estimated that the value of environmental remediation exceeds $100 billion. Alarmingly, if past expenditures on NPL sites are extrapolated across remaining and proposed NPL sites, this total may be significantly higher – well into the trillions of dollars.

It is estimated that more than 4,700 facilities in the United States currently treat, store or dispose of hazardous wastes. Of these, about 3,700 facilities that house approximately 64,000 solid waste management units (SWMUs) may require corrective action. Accidental spillage of hazardous wastes and nuclear materials due to anthropogenic operations or natural disasters has also caused enormous environmental damage as evidenced by the events such as the facility failure in Chernobyl, Ukraine (formerly USSR) in 1986, the effects of Hurricane Katrina that devastated New Orleans, Louisiana in 2005, and the 2011 Tōhoku earthquake and tsunami in Fukushima, Japan.

Adverse Impacts on Public Health

A wide variety of chemicals are present within waste materials, many of which pose a significant environmental concern. Though the **leachate** generated from the wastes may contain toxic chemicals, the concentrations and variety of toxic chemicals are quite small compared to hazardous waste sites. For example, explosives and radioactive wastes are primarily located at Department of Energy (DOE) sites because many of these facilities have been historically used for weapons research, fabrication, testing, and training. Organic contaminants are largely found at oil refineries, or petroleum storage sites, and inorganic and pesticide contamination usually is the result of a variety of industrial activities as well as agricultural activities. Yet, soil and groundwater contamination are not the only direct adverse effects of improper waste management activities – recent studies have also shown that greenhouse gas emissions from the wastes are significant, exacerbating global climate change.

A wide range of toxic chemicals, with an equally wide distribution of respective concentrations, is found in waste streams. These compounds may be present in concentrations that alone may pose a threat to human health or may have a synergistic/cumulative effect due to the presence of other compounds. Exposure to hazardous wastes has been linked to many types of cancer, chronic illnesses, and abnormal reproductive outcomes such as birth defects, low birth weights, and spontaneous abortions. Many studies have been performed on major toxic chemicals found at hazardous waste sites incorporating epidemiological or animal tests to determine their toxic effects.

As an example, the effects of radioactive materials are classified as **somatic** or **genetic**. The **somatic** effects may be immediate or occur over a long period of time. Immediate effects from large radiation doses often produce nausea and vomiting, and may be followed by severe blood changes, hemorrhage, infection, and death. Delayed effects include leukemia, and many types of cancer including bone, lung, and breast cancer. **Genetic** effects have been observed in which gene mutations or chromosome abnormalities result in measurable harmful effects, such as decreases in life expectancy, increased susceptibility to sickness or disease, infertility, or even death during embryonic stages of life. Because of these studies, occupational dosage limits have been recommended by the National Council on Radiation Protection. Similar studies have been completed for a wide range of potentially hazardous materials. These studies have, in turn, been used to determine safe exposure levels for numerous exposure scenarios, including those that consider occupational safety and remediation standards for a variety of land use scenarios, including residential, commercial, and industrial land uses.

Adverse Impacts on the Environment

The chemicals found in wastes not only pose a threat to human health, but they also have profound effects on entire eco-systems. Contaminants may change the chemistry of waters and destroy aquatic life and underwater eco-systems that are depended upon by more complex species. Contaminants may also enter the food chain through plants or microbiological organisms, and higher, more evolved organisms bioaccumulate the wastes through subsequent ingestion. As the contaminants move farther up the food chain, the continued bioaccumulation results in increased contaminant mass and concentration. In many cases, toxic concentrations are reached, resulting in increased mortality of one or more species. As the populations of these species decrease, the natural inter-species balance is affected. With decreased numbers of predators or food sources, other species may be drastically affected, leading to a chain reaction that can affect a wide range of flora and fauna within a specific eco-system. As the eco-system continues to

deviate from equilibrium, disastrous consequences may occur. Examples include the near extinction of the bald eagle due to persistent ingestion of DDT-impacted fish, and the depletion of oysters, crabs, and fish in Chesapeake Bay due to excessive quantities of fertilizers, toxic chemicals, farm manure wastes, and power plant emissions.

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14.2: Waste Management Strategies

The long-recognized hierarchy of management of wastes, in order of preference consists of prevention, minimization, recycling and **reuse**, **biological treatment**, incineration, and landfill disposal (see Figure below).

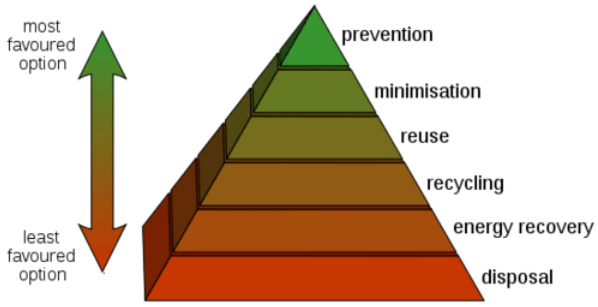


Figure 14.2.1: Hierarchy of Waste Management Figure shows the hierarchy of management of wastes in order or preference, starting with prevention as the most favorable to disposal as the least favorable option. Source: Drstuey via Wikimedia Commons

Waste Prevention

The ideal waste management alternative is to prevent waste generation in the first place. Hence, **waste prevention** is a basic goal of all the waste management strategies. Numerous technologies can be employed throughout the manufacturing, use, or post-use portions of product life cycles to eliminate waste and, in turn, reduce or **prevent pollution**. Some representative strategies include environmentally conscious manufacturing methods that incorporate less hazardous or harmful materials, the use of modern leakage detection systems for material storage, innovative chemical neutralization techniques to reduce reactivity, or water saving technologies that reduce the need for fresh water inputs.

Waste Minimization

In many cases, wastes cannot be outright eliminated from a variety of processes. However, numerous strategies can be implemented to reduce or minimize waste generation. **Waste minimization**, or source reduction, refers to the collective strategies of design and fabrication of products or services that minimize the amount of generated waste and/or reduce the toxicity of the resultant waste. Often these efforts come about from identified trends or specific products that may be causing problems in the waste stream and the subsequent steps taken to halt these problems. In industry, waste can be reduced by reusing materials, using less hazardous substitute materials, or by modifying components of design and processing. Many benefits can be realized by waste minimization or source reduction, including reduced use of natural resources and the reduction of toxicity of wastes.

Waste minimization strategies are extremely common in manufacturing applications; the savings of material use preserves resources but also saves significant manufacturing related costs. Advancements in streamlined packaging reduces material use, increased distribution efficiency reduces fuel consumption and resulting air emissions. Further, engineered building materials can often be designed with specific favorable properties that, when accounted for in overall structural design, can greatly reduce the overall mass and weight of material needed for a given structure. This reduces the need for excess material and reduces the waste associated with component fabrication.

The dry cleaning industry provides an excellent example of product substitution to reduce toxic waste generation. For decades, dry cleaners used tetrachloroethylene, or "perc" as a dry cleaning solvent. Although effective, tetrachloroethylene is a relatively toxic compound. Additionally, it is easily introduced into the environment, where it is highly recalcitrant due to its physical properties. Further, when its degradation occurs, the intermediate daughter products generated are more toxic to human health and the environment.

Because of its toxicity and impact on the environment, the dry cleaning industry has adopted new practices and increasingly utilizes less toxic replacement products, including petroleum-based compounds. Further, new emerging technologies are incorporating carbon dioxide and other relatively harmless compounds. While these substitute products have in many cases been mandated by government regulation, they have also been adopted in response to consumer demands and other market-based forces.

Recycling and Reuse

Recycling refers to recovery of useful materials such as glass, paper, plastics, wood, and metals from the waste stream so they may be incorporated into the fabrication of new products. With greater incorporation of recycled materials, the required use of raw materials for identical applications is reduced. Recycling reduces the need of natural resource exploitation for raw materials, but it also allows waste materials to be recovered and utilized as valuable resource materials. Recycling of wastes directly conserves natural resources, reduces energy consumption and emissions generated by extraction of virgin materials and their subsequent manufacture into finished products, reduces overall energy consumption and greenhouse gas emissions that contribute to the global climate change, and reduces the incineration or landfilling of the materials that have been recycled. Moreover, recycling creates several economic benefits, including the potential to create job markets and drive growth.



Recycling can depend on sorting and separation at the level of the individual users. License: Photo: Lynn Greyling CC0 Public Domain.

Or it can be separated and sorted at a central facility.



Common recycled materials include paper, plastics, glass, aluminum, steel, and wood. Additionally, many construction materials can be reused, including concrete, asphalt materials, masonry, and reinforcing steel. "Green" plant-based wastes are often recovered and immediately reused for mulch or fertilizer applications. Many industries also recover various by-products and/or refine and "re-generate" solvents for reuse. Examples include copper and nickel recovery from metal finishing processes; the recovery of oils, fats, and plasticizers by solvent extraction from filter media such as activated carbon and clays; and acid recovery by spray roasting, ion exchange, or crystallization. Further, a range of used food-based oils are being recovered and utilized in "biodiesel" applications.

Numerous examples of successful recycling and reuse efforts are encountered every day. In some cases, the recycled materials are used as input materials and are heavily processed into end products. Common examples include the use of scrap paper for new

paper manufacturing or the processing of old aluminum cans into new aluminum products. In other cases, reclaimed materials undergo little or no processing prior to their re-use.

Some common examples include the use of tree waste as wood chips, or the use of brick and other fixtures into new structural construction. In any case, the success of recycling depends on effective collection and processing of recyclables, markets for reuse (e.g. manufacturing and/or applications that utilize recycled materials), and public acceptance and promotion of recycled products and applications utilizing recycled materials.

Biological Treatment

Landfill disposal of wastes containing significant organic fractions is increasingly discouraged in many countries, including the United States. Such disposal practices are even prohibited in several European countries. Since landfilling does not provide an attractive management option, other techniques have been identified. One option is to treat waste so that biodegradable materials are degraded and the remaining inorganic waste fraction (known as residuals) can be subsequently disposed or used for a beneficial purpose.

Biodegradation of wastes can be accomplished by using **aerobic** composting, **anaerobic digestion**, or **mechanical biological treatment** (MBT) methods. If the organic fraction can be separated from inorganic material, aerobic composting or anaerobic digestion can be used to degrade the waste and convert it into usable **compost**. For example, organic wastes such as food waste, yard waste, and animal manure that consist of naturally degrading bacteria can be converted under controlled conditions into compost, which can then be utilized as natural fertilizer. Aerobic composting is accomplished by placing selected proportions of organic waste into piles, rows or vessels, either in open conditions or within closed buildings fitted with gas collection and treatment systems. During the process, bulking agents such as wood chips are added to the waste material to enhance the aerobic degradation of organic materials. Finally, the material is allowed to stabilize and mature during a curing process where pathogens are concurrently destroyed. The end-products of the composting process include carbon dioxide, water, and the usable compost material.

Compost material may be used in a variety of applications. In addition to its use as a soil amendment for plant cultivation, compost can be used remediate soils, groundwater, and stormwater. Composting can be labor-intensive, and the quality of the compost is heavily dependent on proper control of the composting process. Inadequate control of the operating conditions can result in compost that is unsuitable for beneficial applications. Nevertheless, composting is becoming increasingly popular; composting diverted 82 million tons of waste material away the landfill waste stream in 2009, increased from 15 million tons in 1980. This diversion also prevented the release of approximately 178 million metric tons of carbon dioxide in 2009 – an amount equivalent to the yearly carbon dioxide emissions of 33 million automobiles.

In some cases, aerobic processes are not feasible. As an alternative, anaerobic processes may be utilized. Anaerobic digestion consists of degrading mixed or sorted organic wastes in vessels under anaerobic conditions. The anaerobic degradation process produces a combination of methane and carbon dioxide (biogas) and residuals (biosolids). Biogas can be used for heating and electricity production, while residuals can be used as fertilizers and soil amendments. Anaerobic digestion is a preferred degradation for wet wastes as compared to the preference of composting for dry wastes. The advantage of anaerobic digestion is biogas collection; this collection and subsequent beneficial utilization makes it a preferred alternative to landfill disposal of wastes. Also, waste is degraded faster through anaerobic digestion as compared to landfill disposal.

Another waste treatment alternative, mechanical biological treatment (MBT), is not common in the United States. However, this alternative is widely used in Europe. During implementation of this method, waste material is subjected to a combination of mechanical and biological operations that reduce volume through the degradation of organic fractions in the waste. Mechanical operations such as sorting, shredding, and crushing prepare the waste for subsequent biological treatment, consisting of either aerobic composting or anaerobic digestion. Following the biological processes, the reduced waste mass may be subjected to incineration.

Incineration

Waste degradation not only produces useful solid end-products (such as compost), degradation by-products can also be used as a beneficial energy source. As discussed above, anaerobic digestion of waste can generate biogas, which can be captured and incorporated into electricity generation. Alternatively, waste can be directly incinerated to produce energy. Incineration consists of

waste combustion at very high temperatures to produce electrical energy. The byproduct of incineration is ash, which requires proper characterization prior to disposal, or in some cases, beneficial re-use. It is widely used in developed countries due to landfill space limitations. It is estimated that about 130 million tons of waste are annually combusted in more than 600 plants in 35 countries. Further, incineration is often used to effectively mitigate hazardous wastes such as chlorinated hydrocarbons, oils, solvents, medical wastes, and pesticides.

Table 14.2.1: Pros and Cons of Incinerators

Pros of Incinerators	Cons of Incinerators
The incinerated waste is turned into energy.	The fly ash (airborne particles) has high levels of toxic chemicals, including dioxin, cadmium and lead.
The volume of waste is reduced.	The initial construction costs are high.

Despite the advantages, incineration is often viewed negatively because of high initial construction costs, and emissions of ash, which is toxic (see Table above). Currently, many 'next generation" systems are being researched and developed, and the USEPA is developing new regulations to carefully monitor incinerator air emissions under the Clean Air Act.

Landfill Disposal

Despite advances in reuse and recycling, landfill disposal remains the primary waste disposal method in the United States. As previously mentioned, the rate of MSW generation continues to increase, but overall landfill capacity is decreasing. New regulations concerning proper waste disposal and the use of innovative liner systems to minimize the potential of groundwater contamination from leachate infiltration and migration have resulted in a substantial increase in the costs of landfill disposal. Also, public opposition to landfills continues to grow, partially inspired by memories of historic uncontrolled dumping practices the resulting undesirable side effects of uncontrolled vectors, contaminated groundwater, unmitigated odors, and subsequent diminished property values.

Landfills can be designed and permitted to accept hazardous wastes in accordance with RCRA Subtitle C regulations, or they may be designed and permitted to accept municipal solid waste in accordance with RCRA Subtitle D regulations. Regardless of their waste designation, landfills are engineered structures consisting of bottom and side liner systems, leachate collection and removal systems, final cover systems, gas collection and removal systems, and groundwater monitoring systems. An extensive permitting process is required for siting, designing and operating landfills. Post-closure monitoring of landfills is also typically required for at least 30 years. Because of their design, wastes within landfills are degraded anaerobically. During degradation, biogas is produced and collected. The collection systems prevent uncontrolled subsurface gas migration and reduce the potential for an explosive condition. The captured gas is often used in cogeneration facilities for heating or electricity generation. Further, upon closure, many landfills undergo "land recycling" and redeveloped as golf courses, recreational parks, and other beneficial uses.

Wastes commonly exist in a dry condition within landfills, and as a result, the rate of waste degradation is commonly very slow. These slow degradation rates are coupled with slow rates of degradation-induced settlement, which can in turn complicate or reduce the potential for beneficial land re-use at the surface. Recently, the concept of bioreactor landfills has emerged, which involves recirculation of leachate and/or injection of selected liquids to increase the moisture in the waste, which in turn induces rapid degradation. The increased rates of degradation increase the rate of biogas production, which increases the potential of beneficial energy production from biogas capture and utilization.

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14.3: Waste Policies

Regulatory Framework in the United States

During the course of the 20th century, especially following World War II, the United States experienced unprecedented economic growth. Much of the growth was fueled by rapid and increasingly complex industrialization. With advances in manufacturing and chemical applications also came increases in the volume, and in many cases the toxicity, of generated wastes. Furthermore, few if any controls or regulations were in place with respect to the handling of toxic materials or the disposal of waste products. Continued industrial activity led to several high-profile examples of detrimental consequences to the environment resulting from these uncontrolled activities. Finally, several forms of intervention, both in the form of government regulation and citizen action, occurred in the early 1970s.

Ultimately, several regulations were promulgated on the state and federal levels to ensure the safety of public health and the environment. With respect to waste materials, the Resource Conservation and Recovery Act (RCRA), enacted by the United States Congress, first in 1976 and then amended in 1984, provides a comprehensive framework for the proper management of hazardous and non-hazardous solid wastes in the United States. RCRA stipulates broad and general legal objectives while mandating the United States Environmental Protection Agency (USEPA) to develop specific regulations to implement and enforce the law. States and local governments can either adopt the federal regulations, or they may develop and enforce more stringent regulations than those specified in RCRA. Similar regulations have been developed or are being developed worldwide to manage wastes in a similar manner in other countries.

The broad goals of RCRA include:

1. the protection of public health and the environment from the hazards of waste disposal
2. the conservation of energy and natural resources
3. the reduction or elimination of waste
4. the assurance that wastes are managed in an environmentally-sound manner (e.g. the remediation of waste which may have spilled, leaked, or been improperly disposed).

It should be noted here that the RCRA focuses only on active and future facilities and does not address abandoned or historical sites. These types of environmentally impacted sites are managed under a different regulatory framework, known as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, or more commonly known as "Superfund."

Solid Waste Regulations

RCRA defines solid waste as any garbage or refuse, sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semi-solid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities. In general, solid waste can be categorized as either **non-hazardous waste** or **hazardous waste**.

Non-hazardous solid waste can be trash or garbage generated from residential households, offices and other sources. Generally, these materials are classified as **municipal solid waste** (MSW)**.** Alternatively, non-hazardous materials that result from the production of goods and products by various industries (e.g. coal combustion residues, mining wastes, cement kiln dust), are collectively known as industrial solid waste. Because they are classified as non-hazardous material, many components of municipal solid waste and industrial waste have potential for recycling and re-use. Significant efforts are underway by both government agencies and industry to advance these objectives.

Hazardous waste, generated by many industries and businesses (e.g. dry cleaners and auto repair shops), is constituted of materials that are dangerous or potentially harmful to human health and the environment. Waste is classified as hazardous if it exhibits at least one of these four characteristics:

- **Ignitability**, which refers to creation of fires under certain conditions; including materials that are spontaneously combustible or those that have a flash point less than 140 $^{\circ}$F.

- **Corrosivity**, which refers to capability to corrode metal containers; including materials with a pH less than or equal to 2 or greater than or equal to 12.5.
- **Reactivity**, which refers to materials susceptible to unstable conditions such as explosions, toxic fumes, gases, or vapors when heated, compressed, or mixed with water under normal conditions.
- **Toxicity**, which refers to substances that can induce harmful or fatal effects when ingested or absorbed, or inhaled.

Radioactive Waste Regulations

Although non-hazardous waste and hazardous waste are regulated by RCRA, nuclear or radioactive waste is regulated in accordance with the Atomic Energy Act of 1954 by the Nuclear Regulatory Commission (NRC) in the United States.

Radioactive wastes are characterized according to four categories:

1. **High-level waste** (HLW)
2. **Transuranic waste** (TRU)
3. **Low-level waste** (LLW)
4. **Mill tailings**

Various radioactive wastes decay at different rates, but health and environmental dangers due to radiation may persist for hundreds or thousands of years.

High-level waste is typically liquid or solid waste that results from government defense related activities or from nuclear power plants and spent fuel assemblies. These wastes are extremely dangerous due to their heavy concentrations of radionuclides, and humans must not come into contact with them.

Transuranic waste mainly results from the reprocessing of spent nuclear fuels and from the fabrication of nuclear weapons for defense projects. They are characterized by moderately penetrating radiation and a decay time of approximately twenty years until safe radionuclide levels are achieved. Following the passage of a reprocessing ban in 1977, most of this waste generation ended. Even though the ban was lifted in 1981, Transuranic waste continues to be rare because reprocessing of nuclear fuel is expensive. Further, because the extracted plutonium may be used to manufacture nuclear weapons, political and social pressures minimize these activities.

Low level wastes include much of the remainder of radioactive waste materials. They constitute over 80 percent of the volume of all nuclear wastes, but only about two percent of total radioactivity. Sources of Low level wastes include all of the previously cited sources of High-level waste and Transuranic waste, plus wastes generated by hospitals, industrial plants, universities, and commercial laboratories. Low level waste is much less dangerous than High-level waste, and NRC regulations allow some very low-level wastes to be released to the environment. Low level wastes may also be stored or buried until the isotopes decay to levels low enough such that it may be disposed of as non-hazardous waste. Low level wastes disposal is managed at the state level, but requirements for operation and disposal are established by the USEPA and NRC. The Occupational Health and Safety Administration (OSHA) is the agency in charge of setting the standards for workers that are exposed to radioactive materials.

International Regulatory Framework

The 1992 Basel Convention

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal first came into force in 1992. The Convention puts an onus on exporting countries to ensure that hazardous wastes are managed in an environmentally sound manner in the country of import.

The Basel Convention places obligations on countries that are party to the Convention. 151 Countries have ratified the Basel Convention as at December 2002. These have obligations to:

- Minimize generation of hazardous waste;
- Ensure adequate disposal facilities are available;
- Control and reduce international movements of hazardous waste;
- Ensure environmentally sound management of wastes; and
- Prevent and punish illegal traffic.

(link is external)

The 1995 Waigani Convention

The Basel Convention establishes a global control system for hazardous wastes being shipped from one country to another. States which are Parties to the Convention must not trade in hazardous wastes with non-Parties but an exception to this is provided for in Article 11 of the Convention, whereby Parties may enter into agreements or arrangements either with other Parties or with non-Parties.

These agreements or arrangements can also set out controls which are different from those prescribed by the Convention itself, provided such controls do not reduce the level of environmental protection intended by the Convention.

The **Waigani Convention** to Ban the Importation into Forum Island Countries of Hazardous and Radioactive Wastes and to Control the Transboundary Movement and Management of Hazardous Wastes within the South Pacific Region) is one such agreement which is entered into force in October 2001.

The main effect of this Convention is to ban the import of all hazardous and radioactive wastes into South Pacific Forum Island Countries. It also enables Australia to receive hazardous wastes exported from South Pacific Forum Island countries which are not Parties to the Basel Convention. There are 24 countries within the coverage area of the Waigani Convention.

As at December 2002, ten parties had ratified the Waigani Convention. These were Australia, Cook Islands, Federated States of Micronesia, Kirribati, New Zealand, Papua New Guinea, Samoa, Solomon Islands, Tuvalu and Vanuatu.

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14.4: Case Study - Electronic Waste and Extended Producer Responsibility

Electronic waste, commonly known as e-waste, refers to discarded electronic products such as televisions, computers and computer peripherals (e.g. monitors, keyboards, disk drives, and printers), telephones and cellular phones, audio and video equipment, video cameras, fax and copy machines, video game consoles, and others (see Figure below).



Figure 14.4.1: Electronic Waste Photograph shows many computers piled up in a parking lot as waste. Source: Bluedisk via Wikimedia Commons

In the United States, it is estimated that about 3 million tons of e-waste are generated each year. This waste quantity includes approximately 27 million units of televisions, 205 million units of computer products, and 140 million units of cell phones. Less than 15 to 20 percent of the e-waste is recycled or refurbished; the remaining percentage is commonly disposed of in landfills and/or incinerated. It should be noted that e-waste constitutes less than 4 percent of total solid waste generated in the United States. However, with tremendous growth in technological advancements in the electronics industry, many electronic products are becoming obsolete quickly, thus increasing the production of e-waste at a very rapid rate. The quantities of e-waste generated are also increasing rapidly in other countries such as India and China due to high demand for computers and cell phones.

In addition to the growing quantity of e-waste, the hazardous content of e-waste is a major environmental concern and poses risks to the environment if these wastes are improperly managed once they have reached the end of their useful life. Many e-waste components consist of toxic substances, including heavy metals such as lead, copper, zinc, cadmium, and mercury as well as organic contaminants, such as flame retardants (polybrominated biphenyls and polybrominated diphenylethers). The release of these substances into the environment and subsequent human exposure can lead to serious health and pollution issues. Concerns have also been raised with regards to the release of toxic constituents of e-waste into the environment if landfilling and/or incineration options are used to manage the e-waste.

Various regulatory and voluntary programs have been instituted to promote reuse, recycling and safe disposal of bulk e-waste. Reuse and refurbishing has been promoted to reduce raw material use energy consumption, and water consumption associated with the manufacture of new products. Recycling and recovery of elements such as lead, copper, gold, silver and platinum can yield valuable resources which otherwise may cause pollution if improperly released into the environment. The recycling and recovery operations have to be conducted with extreme care, as the exposure of e-waste components can result in adverse health impacts to the workers performing these operations. For economic reasons, recycled e-waste is often exported to other countries for recovery operations. However, lax regulatory environments in many of these countries can lead to unsafe practices or improper disposal of bulk residual e-waste, which in turn can adversely affect vulnerable populations.

In the United States, there are no specific federal laws dealing with e-waste, but many states have recently developed e-waste regulations that promote environmentally sound management. For example, the State of California passed the Electronic Waste

Recycling Act in 2003 to foster recycling, reuse, and environmentally sound disposal of residual bulk e-waste. Yet, in spite of recent regulations and advances in reuse, recycling and proper disposal practices, additional sustainable strategies to manage e-waste are urgently needed.

One sustainable strategy used to manage e-waste is extended producer responsibility (EPR), also known as product stewardship. This concept holds manufacturers liable for the entire life-cycle costs associated with the electronic products, including disposal costs, and encourages the use of environmental-friendly manufacturing processes and products. Manufacturers can pursue EPR in multiple ways, including reuse/refurbishing, buy-back, recycling, and energy production or beneficial reuse applications. Life-cycle assessment and life-cycle cost methodologies may be used to compare the environmental impacts of these different waste management options. Incentives or financial support is also provided by some government and/or regulatory agencies to promote EPR. The use of non-toxic and easily recyclable materials in product fabrication is a major component of any EPR strategy. A growing number of companies (e.g. Dell, Sony, HP) are embracing EPR with various initiatives towards achieving sustainable e-waste management.

EPR is a preferred strategy because the manufacturer bears a financial and legal responsibility for their products; hence, they have an incentive to incorporate green design and manufacturing practices that incorporate easily recyclable and less toxic material components while producing electronics with longer product lives. One obvious disadvantage of EPR is the higher manufacturing cost, which leads to increased cost of electronics to consumers.

There is no specific federal law requiring EPR for electronics, but the United States Environmental Protection Agency (USEPA) undertook several initiatives to promote EPR to achieve the following goals: (1) foster environmentally conscious design and manufacturing, (2) increase purchasing and use of more environmentally sustainable electronics, and (3) increase safe, environmentally sound reuse and recycling of used electronics. To achieve these goals, USEPA has been engaged in various activities, including the promotion of environmental considerations in product design, the development of evaluation tools for environmental attributes of electronic products, the encouragement of recycling (or *e*-cycling), and the support of programs to reduce e-waste, among others. More than 20 states in the United States and various organizations worldwide have already developed laws and/or policies requiring EPR in some form when dealing with electronic products. For instance, the New York State Wireless Recycling Act emphasizes that authorized retailers and service providers should be compelled to participate in take-back programs, thus allowing increased recycling and reuse of e-waste. Similarly, Maine is the first U.S. state to adopt a household e-waste law with EPR.

In Illinois, Electronic Products Recycling & Reuse Act requires the electronic manufacturers to participate in the management of discarded and unwanted electronic products from residences. The Illinois EPA has also compiled e-waste collection site locationswhere the residents can give away their discarded electronic products at no charge. Furthermore, USEPA compiled a list of local programs and manufacturers/retailers that can help consumers to properly donate or recycle e-waste.

Overall, the growing quantities and environmental hazards associated with electronic waste are of major concern to waste management professionals worldwide. Current management strategies, including recycling and refurbishing, have not been successful. As a result, EPR regulations are rapidly evolving throughout the world to promote sustainable management of e-waste. However, neither a consistent framework nor assessment tools to evaluate EPR have been fully developed.

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14.5: Resources

Summary

Many wastes, such as high-level radioactive wastes, will remain dangerous for thousands of years, and even MSW can produce dangerous leachate that could devastate an entire eco-system if allowed infiltrate into and migrate within groundwater. In order to protect human health and the environment, environmental professionals must deal with problems associated with increased generation of waste materials. The solution must focus on both reducing the sources of wastes as well as the safe disposal of wastes. It is, therefore, extremely important to know the sources, classifications, chemical compositions, and physical characteristics of wastes, and to understand the strategies for managing them. Waste management practices vary not only from country to country, but they also vary based on the type and composition of waste. Regardless of the geographical setting of the type of waste that needs to be managed, the governing principle in the development of any waste management plan is resource conservation. Natural resource and energy conservation is achieved by managing materials more efficiently. Reduction, reuse, and recycling are primary strategies for effective reduction of waste quantities. Further, proper waste management decisions have increasing importance, as the consequences of these decisions have broader implications with respect to greenhouse gas emissions and global climate change. As a result, several public and private partnership programs are under development with the goal of waste reduction through the adoption of new and innovative waste management technologies. Because waste is an inevitable by-product of civilization, the successful implementation of these initiatives will have a direct effect on the enhanced quality of life for societies worldwide.

Review Questions

1. How is hazardous waste defined according to the Resource Conservation and Recovery Act (RCRA)? In your opinion, is this definition appropriate? Explain.
2. Explain specific characteristics of radioactive and medical wastes that make their management more problematic than MSW.
3. Compare and contrast environmental concerns with wastes in a rural versus urban setting.
4. What are the pros and cons of various waste management strategies? Do you agree or disagree with the general waste management hierarchy?
5. Explain the advantages and disadvantages of biological treatment and incineration of wastes.

Attributions

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

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CHAPTER OVERVIEW

15: Economics and Urbanization

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15.1: 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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15.2: 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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15.3: 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 (see Figure below) and fragmentation of the urban area (see Figure below), 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 15.3.1: Sprawl vs. Compact Cities. An often cited example of urban sprawl is Atlanta, GA (US), which has a similar population as Barcelona but occupies an urban area that is 26 times as large

Health

If communities are not walkable or bikeable, we need to drive to schools, shops, parks, entertainment, play dates, etc. Thus we become more sedentary. Residents of sprawling counties were likely to walk less during leisure time and weigh more than residents of compact counties. A sedentary lifestyle increases the risk of overall mortality, cardiovascular disease, and some types of cancer. 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

below), and in particular high energy consumption rates that are associated with lower population densities, characteristic of sprawling environments, dependent on lengthy distribution systems that undermine efficient energy use.

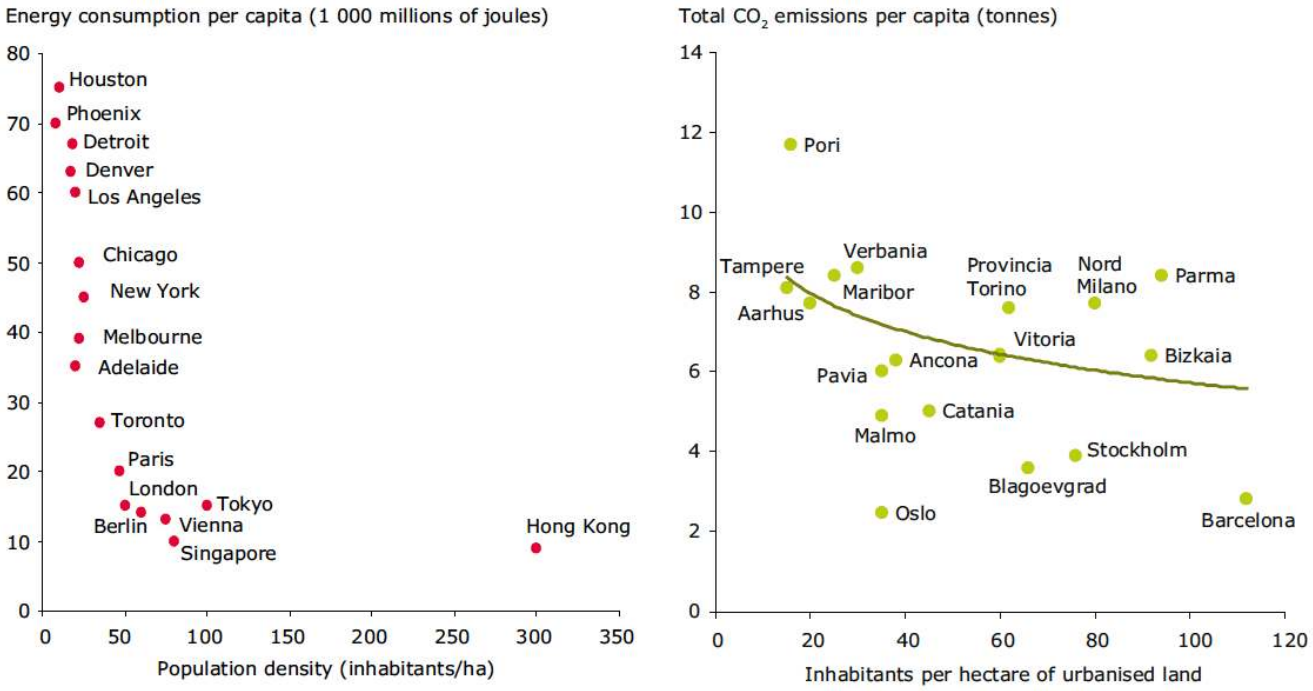


Figure 15.3.2: Left - Population density and energy consumption, selected World cities. Right - Population density and CO2 emissions, selected European cities.

Transport related energy consumption in cities depends on 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.


Figure 15.3.3: Sprawling area.

Natural and Protected areas

The impacts of sprawl on natural areas are significant. The considerable impact of urban sprawl on natural and protected areas is exacerbated by the increased proximity and accessibility of urban activities to natural areas, imposing stress on ecosystems and species through noise and air pollution. Immediate impacts such as the loss of agricultural and natural land or the fragmentation of forests (Figure below), wetlands and other habitats are well known direct and irreversible impacts. Urban land fragmentation, with the disruption of migration corridors for wildlife species, isolates these populations and can reduce natural habitats to such an extent that the minimum area required for the viability of species populations is no longer maintained.


Figure 15.3.4: Forrest fragmentation.

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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15.4: 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. It promotes the development of socially and environmentally sustainable city districts. The following principles of green urbanism offer practical steps on the path to sustainable cities, harmonizing growth and usage of resources.



Figure 15.4.1: Green Urbanism.

Climate and Context

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. The various aspects of this principle include: Climatic conditions, which are seen as the fundamental influence for form-generation in the design of any project; understanding the site and its context, which is essential at the beginning of every sustainable design project; optimizing orientation and compactness to help reduce the city district's heat gain or losses; achieving a city with minimized environmental footprint by working with the existing landscape, topography and resources particular to the site, and the existing micro-climate of the immediate surroundings. Maintaining complexity in the system is always desirable (be it biodiversity, eco-system or neighborhood layout), and a high degree of complexity is always beneficial for society. Enhancing the opportunities offered by topography and natural setting leads

to a city well adapted to the local climate and its eco-system. We can use the buildings' envelope to filter temperature, humidity, light, wind and noise. Due to the different characteristics of every location, each city district has to 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.

Renewable Energy for Zero CO_2 Emissions

The various aspects of this principle include: Energy supply systems and services, as well as energy efficient use and operation, promoting increased use of renewable power, and perhaps natural gas as a transition fuel in the energy mix, but always moving quickly away from heavy fossil-fuels such as coal and oil; and the transformation of the city district from an energy consumer to an energy producer, with local solutions for renewables and the increasing de-carbonizing of the energy supply. The supply of oil will last shorter than the life-expectancy of most buildings. The local availability of a renewable source of energy is the first selection criteria for deciding on energy generation. In general, a well-balanced combination of energy sources can sensibly secure future supply. A necessary aim is also to have a distributed energy supply through a decentralized system, utilizing local renewable energy sources. This will transform city districts into local power stations of renewable energy sources, which will include solar 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 CHP and solar cooling. That is to say, there should be on-site electrical generation and energy storage in combination with a smart grid, which integrates local solar and wind generation, utilizing energy-efficiency in all its forms. Solar hot water systems would be compulsory. Co-generation technology utilizes waste heat through CHP 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. Eco-districts 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 can be achieved by using exchange, storage and cascading (exergy) principles. It is, therefore, essential that the fossil-fuel powered energy and transportation systems currently supporting our cities are rapidly turned into systems that are supplied by renewable energy sources. High building insulation, high energy-efficiency standards and the use of smart metering technology is essential, so that if a part of an office building is not in use, the intelligent building management system will shut down lights and ventilation.

Zero-Waste

Sustainable waste management means to turn waste into a resource. All cities should adopt nature's zero-waste management system (See Box below). Zero-waste urban planning includes reducing, recycling, reusing and composting waste to produce energy. All material flows need to be examined and fully understood, and special attention needs to be given to industrial waste and e-waste treatment. We need to plan for recycling centers, for zero landfill and 'eliminating the concept of waste' and better understanding nutrient flows. Eco-districts are neighborhoods where we 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) need to be healthy and fully-recyclable.

Waste prevention is always better than the treatment or cleaning-up after waste is formed. Some other systems that need to be put in place are: the remanufacturing of metals, glass, plastics, paper into new products needs to be a routine (without down-grading the product); waste-to-energy strategies are needed for residual waste; and an `extended producer responsibility' clause is needed for all products. In this context of waste, better management of the nitrogen cycle has emerged as an important topic: to restore the balance to the nitrogen cycle by developing improved fertilization technologies, and technologies in capturing and recycling waste. Controlling the impact of agriculture on the global cycle of nitrogen is a growing challenge for sustainable development. Essentially, we need to become (again) a *recycling society*, where it is common that around 60 to 90 per cent of all waste is recycled and composted.

Water

The various aspects of this principle include, in general, reducing water consumption, finding more efficient uses for water resources, ensuring good water quality and the protection of aquatic habitats. The city can be used as a water catchment area by educating the population in water efficiency, promoting rainwater collection (see Figure below) and using wastewater recycling and storm water harvesting techniques. Storm water and flood management concepts need to be adopted as part of the urban design, and this includes storm water run-offs and improved drainage systems and the treatment of wastewater.



Figure 15.4.2: Description of Rainwater Harvesting Techniques (1) and a Sample Dual-Flush Water-Efficient Toilet (2) at at a Rio de Janeiro Hardware Store.

As part of the eco-district's adequate and affordable health care provisions, it needs to ensure the supply of safe water and sanitation. This includes such things as algae and bio-filtration systems for grey water and improving the quality of our rivers and lakes so that they are fishable and swimmable again. An integrated urban water cycle planning and management system that includes a high-performance infrastructure for sewage recycling (grey and black water recycling), 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.

Landscape, Gardens and Urban Biodiversity

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. Ready access to these green spaces (See figure below): public parks, gardens, with opportunities for leisure and recreation, are essential components of a healthy city. As is arresting the loss of biodiversity by enhancing the natural environment and landscape, and planning the city using ecological principles based on natural cycles (not on energy-intensive technology) as a guide, and increasing urban vegetation. A city that preserves and maximizes its open spaces, natural landscapes and recreational opportunities is a more healthy and resilient city. The sustainable city also needs to introduce inner-city gardens, **urban farming** and **green roofs** in all its urban design projects (using the city for food supply).



Figure 15.4.3: Urban Farming in Chicago. Some new crops being started, protected by shade cloth barriers to the west.

It needs to maximize the resilience of the eco-system through urban landscapes that mitigate the `urban heat island' (UHI) effect, using plants for air-purification and urban cooling. Further, the narrowing of roads, which calms traffic and lowers the UHI effect, allows for more (all-important) tree planting. Preserving green space, gardens and farmland, maintaining a green belt around the city, and planting trees everywhere (including golf courses), as trees absorb CO_2, is an important mission.

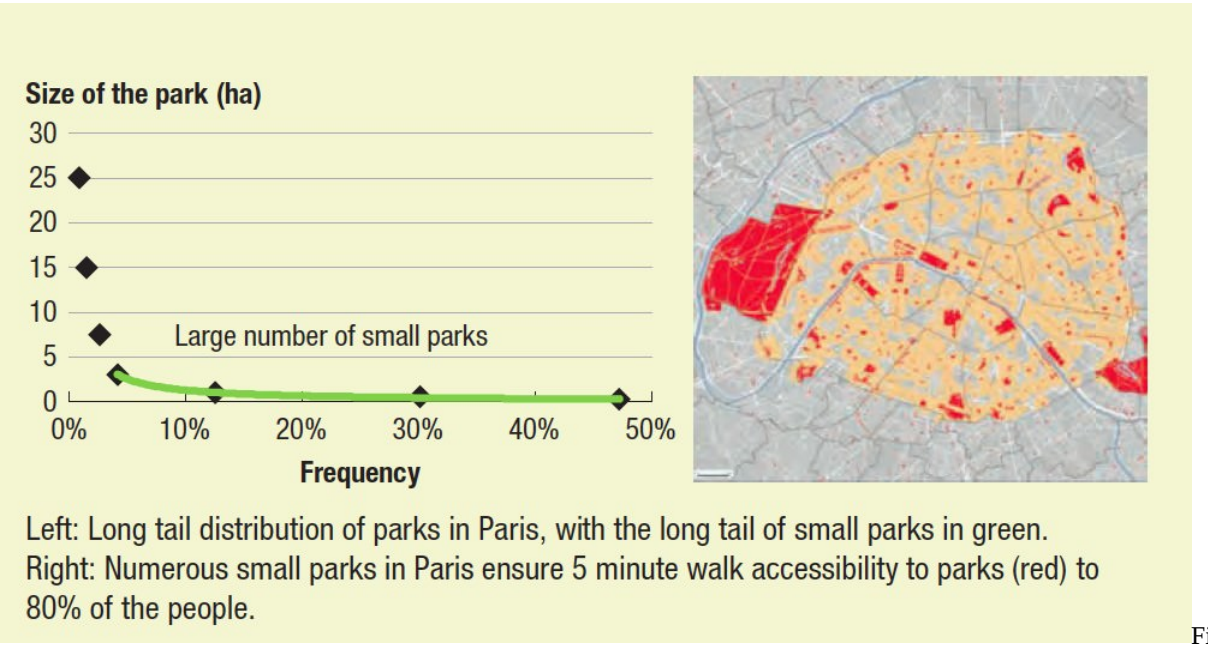


Figure 15.4.4: Green spaces are an essential feature of energy efficient and livable cities. However, many urban policies concerning green spaces in emerging countries' cities boil down to a predetermined percentage of green space. What really matters is access and proximity of green spaces with diversified social activities instead of proportion only. The spatial distribution of green spaces in Paris results from policies and regulations that have ensured that every citizen lives less than 400 m from a public park, square, or garden. This target has been reached whereas green spaces only represent 5 percent of the urban area. 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 (300 green spaces less than ó ha). As a comparison, green spaces in Beijing represent 30 percent of the urban area. Most of the green spaces are very big parks, and the long tail of small parks is lacking. As a result, residents live more than 3 km away from public parks on average.

As is conserving natural resources, respecting natural energy streams and restoring stream and river banks, maximizing species diversity. At home, we need to de-pave the driveway or tear up parking lots. In all urban planning, we need to maintain and protect the existing eco-system that stores carbon (e.g. through a grove or a park), and plan for the creation of new carbon storage sites by increasing the amount of tree planting in all projects. The increase in the percentage of green space as a share of total city land is to be performed in combination with densification activities.

Sustainable Transport and Good Public space: Compact and Poly-Centric Cities

Good access to basic transport services is crucial, as it helps to reduce automobile dependency, as does reducing the need to travel. We need to see integrated non-motorized transport, such as cycling or walking, and, consequently, bicycle/pedestrian-friendly environments, with safe bicycle ways, free rental bike schemes and pleasant public spaces. It is important to identify the optimal transport mix that offers inter-connections for public transport and the integration of private and public transport systems.

Some ideas here include: eco-mobility concepts and smart infrastructure (electric vehicles); integrated transport systems (bus transit, light railway, bike stations); improved public space networks and connectivity, and a focus on transport-oriented development. It is a fact that more and wider roads result in more car and truck traffic, and CO_2 emissions, and also allows for sprawling development and suburbs that increases electricity-demand and provides less green space. The transport sector is responsible for causing significant greenhouse-gas emissions (over 20 per cent). To combat this effect we need to change our lifestyles by, for example, taking public transport, driving the car less, or car-pooling. Alternatively, we can ride a bike or walk, if the city district has been designed for it. Personal arrangements have the potential to reduce commuting and to boost community spirit. We want a city district which is well-connected for pedestrians, a city with streetscapes that encourage a healthy, active lifestyle and where residents travel less and less by car.

Density and Retrofitting of Existing Districts

The various aspects of this principle include: encouraging the densification of the city centre through mixed-use urban infill (see Figure below), 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.

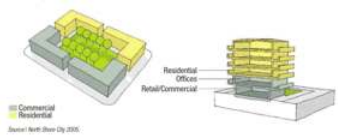


Figure 15.4.5: Mixed Use on the Block and Building Scale.

Consideration will need to be given to better land-use planning to reduce the impact of urban areas on agricultural land and landscape; to 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. Here, examples of rapid development are being provided by Asian cities. Special strategies are also needed for small and medium-sized towns due to their particular milieu, and creative concepts are needed for the particular vulnerabilities of Small Island States and coastal cities. Public space upgrading through **urban renewal** programs will bring people back to the city centre. This will need some strategic thinking about how to use brownfield and greyfield developments and also the adaptive reuse of existing buildings. Remodeling and re-energizing existing city centers to bring about diverse and vibrant communities requires people to move back into downtown areas. This can be achieved through mixed-use urban infill projects, building the "city above the city" by converting low density districts into higher density communities; and by revitalizing underutilized land for community benefit and affordable housing.

Green Buildings and Districts, Using Passive Solar Design Principles.

The various aspects of this principle include: low-energy, zero-emission designs, applying best 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.

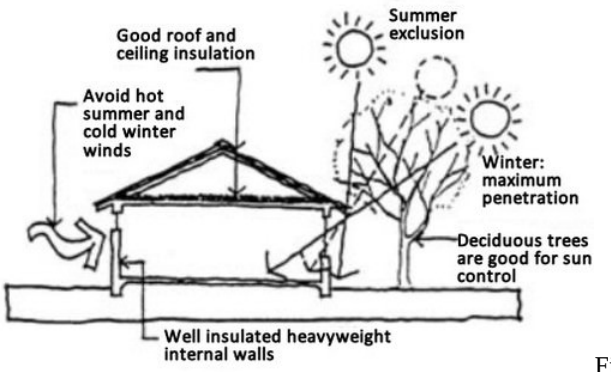


Figure 15.4.6: Passive Solar Design

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.

Local and Sustainable Materials with Less Embodied Energy

The various aspects of this principle include: advanced materials technologies, using opportunities for shorter supply chains, where all urban designs focus on local materials and technological know-how, such as regional timber in common use. Affordable housing can be achieved through modular prefabrication. **Prefabrication** (Figure below) has come and gone several times in modern architecture, but this time, with closer collaboration with manufacturers of construction systems and building components in the design phase, the focus will be on sustainability. We need to support innovation and be aware of sustainable production and consumption, the embodied energy of materials and the flow of energy in closing life-cycles. We need to emphasize green manufacturing and an economy of means, such as process-integrated technologies that lead to waste reduction. It is more environmentally friendly to use lightweight structures, enclosures and local materials with less embodied energy, requiring minimal transport. We need improved material and system specifications, supported by research in new materials and technological innovation; reduced material diversity in multi-component products to help facilitate the design for resource recovery, disassembly, value retention, and the possibility of reusing entire building components. Success in this area will increase the long-term durability of buildings, reduce waste and minimize packaging.

Casa Aqua


Figure 15.4.7

In April 2010, a prototype AQUA house for low-income families was exhibited in São Paulo. It measures 40 square meters and has a construction cost of R$45,000 (11,000 USD). Some of the sustainable solutions adopted include a rainwater reuse system, consisting of a cistern and permeable soil; a solar water heater; fiber-cellulose shingles; and soil-cement bricks, which are dimensioned and prefabricated to allow for faster assembly and do not use mortar, thereby reducing costs.

A sloped roof with skylights was designed to take advantage of natural light and ventilation. The 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.

Livability, Healthy Communities and Mixed-Use Programs

Land use development patterns are the key to sustainability. A mixed-use (and mixed-income) city delivers more social sustainability and social inclusion, and helps to repopulate the city centre. Demographic changes, such as age, are a major issue for urban design. It is advantageous for any project to maximize the diversity of its users. Different sectors in the city can take on different roles over a 24 hours cycle; for example, the Central Business District is used for more than just office work. In general we want **connectivity** (see Figure below**)**, compact communities, for a livable city, applying mixed-use concepts and strategies for housing affordability, and offering different typologies for different housing needs.

	Turi, Estonia	Barcelona, Spain	Paris, France	Ginza, Tokyo	Pudong in Shanghai, China	Towers North in Beijing, China
						
Intersections per km²	152	103	133	211	17	14
Distance between intersections (m)	80	130	150	43	280	400

Figure 15.4.8: The Absence of Connectivity and Fine Grain in Chinese Urban Developments. The pictures illustrate the size of blocks and impacts on connectivity of a series of cities in Europe, Japan, and China. It shows the absence of connectivity and the increase of average distances between intersections in recent urban developments in China.

To this end we need affordable and livable housing together with new flexible typologies for inner-city living. These mixed-use neighborhoods (of housing types, prices and ownership forms) have to avoid gentrification and provide affordable housing with

districts inclusive for the poor and the rich, young and old, and workers of all walks of life, and also provide secure tenure (ensuring ‘aging in place’). Mixed land uses are particularly important as it helps reduce traffic. Master plans should require all private developments to contain 40 to 50 per cent of public (social) housing, and have it integrated with private housing. Higher densities should centre on green TODs. Essentially, these changes will aim to introduce more sustainable lifestyle choices, with jobs, retail, housing and a city campus being close by with IT and telecommuting from home significantly helping to reduce the amount of travel.

 Figure 15.4.9: Telecommuting.

By integrating a diverse range of economic and cultural activities, we avoid mono-functional projects, which generate a higher demand for mobility. Green businesses would be supported through the use of ethical investments to generate funding.

Local Food and Short Supply Chains

The various aspects of this principle include: local food production; regional supply; an emphasis on urban farming and agriculture, including `eat local’ and `slow food’ initiatives. The sustainable city makes provision for adequate land for food production in the city, a return to the community and to the allotment gardens of past days, where roof gardens become an urban market garden. It is essential that we bridge the urban-rural disconnect and move cities towards models that deal in natural eco-systems and healthy food systems.

The people of the eco-city would garden and farm locally, sharing food, creating compost with kitchen scraps and garden clippings and growing `community’ vegetables. Buying and consuming locally will be necessary to cut down on petrol-based transport. Such things as re-using bags and glass containers, paper recycling and the cost of food processing will need reconsideration. We will need to reduce our consumption of meat and other animal products, especially shipped-in beef, as the meat cycle is very intensive in terms of energy and water consumption and herds create methane and demand great quantities of electricity. Perhaps as much as 50 per cent of our food will need to be organically produced, without the use of fertilizers or pesticides made from oil, and grown in local allotments.

Cultural Heritages, Identity and Sense of Place

All sustainable cities aim for air quality, health and pollution reduction, to foster resilient communities, 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.

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.

Education, Research and Knowledge

The various aspects of this principle include: technical training and up-skilling, research, exchange of experiences, knowledge dissemination through research publications about ecological city theory and sustainable design. Primary and secondary teaching programs need to be developed for students in such subjects as waste recycling, water efficiency and sustainable behavior. Changes in attitude and personal lifestyles will be necessary. The city is a hub of institutions, such as galleries and libraries and museums, where knowledge can be shared. We must provide sufficient access to educational opportunities and training for the citizenry, thus increasing their chances of finding green jobs. Universities can act as `think tanks' for the transformation of their cities. We also need to redefine the education of architects, urban designers, planners and landscape architects. Research centers for sustainable urban development policies and best practice in eco-city planning could be founded, where assessment tools to measure environmental performance are developed and local building capacity is studied.

Strategies for Cities in Developing Countries

Developing and emerging countries have their own needs and require particular strategies, appropriate technology transfers and funding mechanisms. Cities in the developing world cannot have the same strategies and debates as cities in the developed world. Similarly, particular strategies for emerging economies and fast-growing cities are required, as is the problem of informal settlements and urban slums and slum upgrading programs. Low-cost building and mass housing typologies for rapid urbanization are required in cooperation with poverty reduction programs. It is essential that we train local people to empower communities, creating new jobs and diversifying job structures, so as not to focus on only one segment of the economy (e.g. tourism). Achieving more sustainable growth for Asian metropolitan cities is a necessity. Combating climate change, which was mainly caused through the emissions by industrialized nations and which is having its worst effect in poorer countries in Africa, Asia and Latin America, with a focus on Small Island States, is a priority.

Contributors and Attributions

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15.5: 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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15.6: Resources

Summary

Environmental and natural resource economists study the tradeoffs associated with one of the most important scarce resources we have—nature. Economic activity generally affects the environment, usually negatively. Natural resources are used, and large amounts of waste are produced. These side effects can be seen as ways in which the actions of a producer impact the well being of a bystander. The market fails to allocate adequate resources to address such external costs because it is only concerned with buyers and sellers, not with the well being of the environment. Only direct costs are considered relevant. External costs are harmful social or environmental effects caused by the production or consumption of economic goods. A cost-benefit analysis provides an estimate of the most economically efficient level of pollution reduction that is practical. Environmental laws today encompass 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. 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 and a treaty that banned the ocean dumping of wastes.

Review Questions

1. How do externalities cause market outcomes not to be efficient?
2. How are the free rider problem and the common pool resource problem related to basic problems of externalities?
3. What is discounting, and how do we use it in calculating the costs and the benefits of a project that has effects over a long period of time?
4. Why is discounting controversial?
5. How does cost-benefit analysis complement some of the other measures people use to evaluate a policy or project?
6. List major international environmental laws of the past two decades.

Attributions

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

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CHAPTER OVERVIEW

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16.1: 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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16.2: The Evolution of Environmental Policy in the United States - Chapter Introduction

Introduction

It is not uncommon 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 Brundtland Report) when it was first presented in 1987. Certainly the period during 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 as discussed in Chapter 2, 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 the many problems that confront humanity at this time. It is also true that it was among the first widely disseminated writings to define and use the modern meaning of the term "sustainable" through the often-quoted concept of "sustainable development." However, it would be a mistake to conclude that sustainability as a mental construct and policy framework for envisioning the relationship of humans and nature came into being suddenly and at a single moment in time. Most environmental historians who have studied U.S. policy have discerned at least three distinct periods during which new concepts and ideas, scientific understandings, technological advances, political institutions, and laws and regulations came or were brought into being in order to understand and manage human impacts on the environment. 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 to create what we now refer to as the sustainability paradigm. In this chapter we will explore the roots of modern sustainability (Module 4.2), see how our thinking about the environment has shifted (Module 4.3), and examine the ways that our environmental public policies have changed through time (Module 4.4). Along the way it is important to understand that this has been an evolutionary process and that these environmental "eras," while reflecting the norms, attitudes, and needs of the day, are still very much embodied within the modern concept of sustainability.

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16.3: 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 (see Figures 3.3.3 and 3.3.4 in the last section).

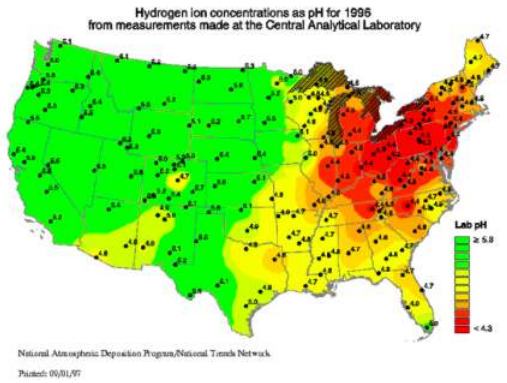


Figure shows the distribution in rainfall pH in the United States for the year 1996. *Source: National Atmospheric Deposition Program/National Trends Network via National Park Service.*

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 16.3.1 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 16.3.1 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 16.3.1 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
Conceptual Model	Expansion vs. preservation	Command-and-control	Systems/life cycle approach
Disciplinary Approach	Disciplinary and insular	Multidisciplinary	Interdisciplinary/Integrative

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16.4: Tragedy of the Commons- a deeper look

Learning Objectives

After reading this module, students should be able to

- know how economists define environmental outcomes that make society as well off as possible.
- understand what externalities are, and how they can lead to outcomes with too much pollution and resource exploitation.
- be able to define public goods and common-property resources, and understand how those things are prone to under-provision and over-exploitation, respectively.

Introduction

To identify and solve environmental problems, we need to understand what situations are actually problems (somehow formally defined) and what circumstances and behaviors cause them. We might think that it is easy to recognize a problem—pollution is bad, saving natural resources is good. However, critical thinking often reveals snap judgments to be overly simplistic. Some examples help to illustrate this point.

- **Running out!** Oil is a depletable resource, and many people worry that rapid extraction and use of oil might cause us to run out. But would it really be a bad thing to use up all the oil as long as we developed alternative energy technologies to which we could turn when the oil was gone? Is there any intrinsic value to keeping a stock of oil unused in the ground? Running out of oil someday may not be a problem. However, subsidies for oil extraction might cause us to run out more quickly than is socially optimal. Other inefficiencies arise if multiple companies own wells that tap the same pool of oil, and each ends up racing to extract the oil before the others can take it away—that kind of race can increase total pumping costs and reduce the total amount of oil that can be gleaned from the pool.
- **Biological pollution!** Horror stories abound in the news about the havoc raised by some nonnative animal and plant species in the United States. Zebra mussels clog boats and industrial pipes, yellow star thistle is toxic to horses and reduces native biodiversity in the American West, and the emerald ash borer kills ash trees as it marches across the landscape. From the current tone of much media and scientific discourse about nonnative species, one could conclude that all nonnative species are problems. But does that mean we should forbid farmers in the U.S from growing watermelons, which come from Africa? Or should we ship all the ring-necked pheasants back to Eurasia whence they originally came, and tell North Dakota to choose a new state bird? The costs and benefits of nonnative species vary greatly – one policy approach is not likely to apply well to them all.

This section first explains the way economists think about whether an outcome is good. Then it describes some of the features of natural resources and environmental quality that often trigger problematic human behaviors related to the environment.

Efficiency and Deadweight Loss

Ask anyone who lived during the centrally-planned, nonmarket economy years of the Soviet Union—markets are very good at many things. When a product becomes scarcer or more costly to produce we would like to send signals to consumers that would cause them to buy less of that thing. If an input is more valuable when used to produce one good than another, we would like to send signals to firms to make sure that input is put to its best use. If conditions are right, market prices do these useful things and more. Markets distribute inputs efficiently through the production side of the economy: they ensure that plant managers don't need to hoard inputs and then drive around bartering with each other for the things they need to make their products, and they arrange for efficient quantities of goods to be produced. Markets also distribute outputs among consumers without surpluses, shortages, or large numbers of bathing suits being foisted upon consumers in Siberia.

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 (Q_{market} in Figure 16.4.1), it is also true that marginal benefit equals marginal cost.

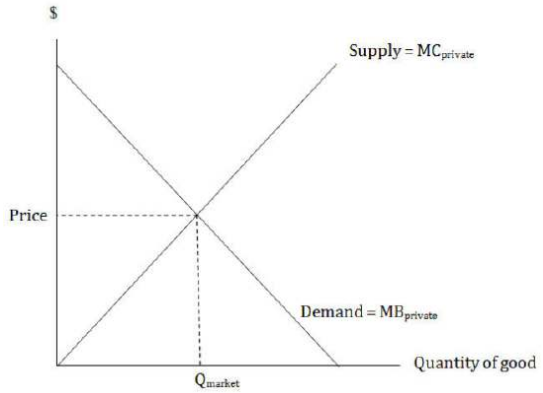


Figure 16.4.1 Market Equilibrium. A private market equilibrates at a price such that the quantity supplied equals the quantity demanded, and thus private marginal cost equals private marginal benefit. *Source:* Amy Ando

Even depletable resources such as oil would be used efficiently by a well-functioning market. It is socially efficient to use a depletable 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 depletable resource to the backstop. We see this with copper; high prices of depletable 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. That behavior can sometimes yield outcomes that maximize total social welfare even if individual agents are only seeking to maximize their own personal well-being, because self-interested trades lead the market to settle where aggregate marginal benefits equal aggregate marginal costs and thus total net benefits are maximized.

However, people and companies do not always bear the full costs and benefits associated with the actions they take. 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. For example, if a student cheats on an exam, that student might get a higher grade. However, if the class is graded on a curve, all the other students will get lower grades. And if the professor learns that cheating happened, she might take steps to prevent cheating on

the next exam that make the testing environment more unpleasant for all the students (no calculators allowed, no bathroom breaks, id checks, etc.). Negative externalities are rampant in environmental settings:

- 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.



Figure 16.4.2 Negative Externality: Smog. A NASA photograph of the atmosphere over upstate New York, with Lake Eire (top) and Lake Ontario (bottom) featured. Both natural, white clouds and man-made smog (grey clouds below) are visible. The smog is an example of a negative externality, as the cost of the pollution is borne by everyone in the region, not just by the producers. *Source: Image Science and Analysis Laboratory, NASA-Johnson Space Center*

In situations where an action or good has a negative externality, the private marginal cost that shapes the behavior of an agent is lower than the marginal cost to society as a whole, which includes the private marginal cost and the external environmental marginal cost.

Conversely, a positive externality is a benefit associated with an action that is not borne by the person who chooses to take that action. Students who get flu shots in October, for example, gain a private benefit because they are less likely to get the flu during the winter months. However, their classmates, roommates, and relatives also gain some benefit from that action because inoculated students are less likely to pass the flu along to them. Positive externalities exist in the world of actions and products that affect the environment:

- 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.

In situations where an action or good has a positive externality, the private marginal benefit that shapes the behavior of an agent is lower than the marginal benefit to society as a whole, which includes the private marginal benefit and the external environmental marginal benefit.

Public Goods and Common-pool Resources

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 hot dog 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 stratospheric ozone layer protects everyone on earth from solar UV radiation

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 hot dog 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 nonexcludable. 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 regrowth 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 overharvesting of fisheries (see 8.3), 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. Elinor Ostrom’s Nobel prize-winning body of work, for example, has studied cases of common-pool resources that were not over-exploited because of informal social institutions.

Glossary

common pool resource

A resource that is open to all users, but which is highly rival in use.

cost-effective

As inexpensive as possible; cost minimizing.

deadweight loss

The extent to which net benefits are lower than they could be.

efficient

Having the feature that net benefits are maximized.

free rider

A person who does not contribute to a public good in hopes that they can benefit from provision by other people.

marginal benefit

The additional benefit of doing one more unit of something.

marginal cost

The additional cost of doing one more unit of something.

market failure

A condition that causes a market not to yield the efficient outcome.

negative externality

A cost that is borne by someone who did not agree to the activity that caused the cost.

net benefits

The difference between total benefits and total costs.

normative analysis

A study of how things should be.

positive analysis

A study of how things are.

positive externality

A benefit that accrues to someone who did not agree to the activity that caused the benefit.

public good

A good with two features: (i) it has a benefit that does not diminish with the number of people enjoying it, and (ii) no one can be excluded from consuming it.

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welfare

Broadly defined, welfare is well-being.

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16.5: Case Study- Marine Fisheries

Fisheries are classic common-pool resources. The details of the legal institutions that govern access to fisheries vary around the globe. However, the physical nature of marine fisheries makes them prone to overexploitation. Anyone with a boat and some gear can enter the ocean. One boat's catch reduces the fish available to all the other boats and reduces the stock available to reproduce and sustain the stock available in the following year. Economic theory predicts that the market failure associated with open access to a fishery will yield socially excessive levels of entry into the fishery (too many boats) and annual catch (too many fish caught) and inefficiently low stocks of fish (Beddington, Agnew, & Clark, 2007).

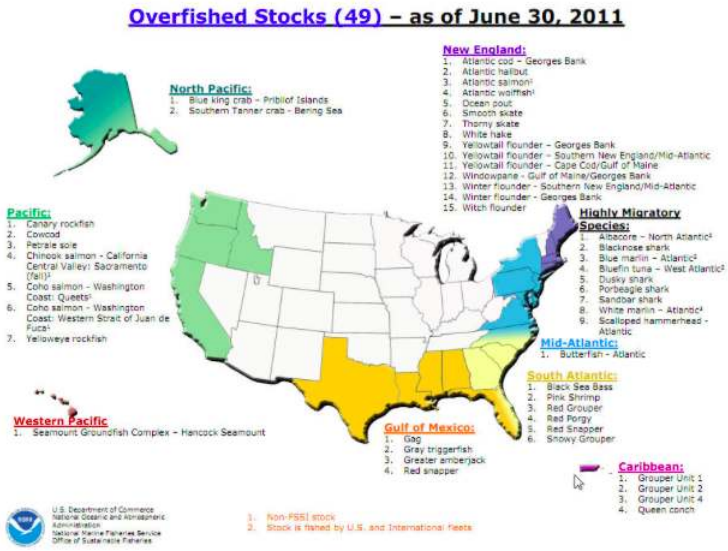


Figure 16.5.1 *Source: National Oceanic and Atmospheric Administration*

Unfortunately, the state of fisheries around the globe seems to indicate that the predictions of that theory are being borne out. Bluefin tuna are in danger of extinction. Stocks of fish in once-abundant fisheries such as North Atlantic cod and Mediterranean swordfish have been depleted to commercial (and sometimes biological) exhaustion (Montaigne, 2007). Scientists have documented widespread collapse of fish stocks and associated loss of marine biodiversity from overfishing; this devastates the ability of coastal and open-ocean ecosystems to provide a wide range of ecosystem services such as food provisioning, water filtration, and detoxification (Worm et al., 2006). Scholars have documented isolated cases such as the "lobster gangs" of coastal Maine where communal informal management prevented overexploitation of the resource (Acheson, 1988), but such cases are the exception rather than the rule.

Early efforts to control overfishing used several kinds of regulations on quotas, fishing effort, and gear. For example, fishing boats are forbidden in some places from using conventional longlines because that gear yields high levels of bycatch and kills endangered leatherback turtles. Some forms of fishery management limit the number of fish that can be caught in an entire fishery. Under a total allowable catch (TAC) system, fishers can fish when and how they want, but once the quota for the fishery has been met, fishing must stop until the next season. Unfortunately, TAC policies do not solve the underlying problem that fishermen compete for the fish, and often yield perverse incentives and undesirable outcomes such as overcapitalization of the industry (Beddington, Agnew, & Clark, 2007) and races between fishing boat crews to catch fish before the quota is reached. In the well-known case of the Alaskan halibut fishery, the race became so extreme that the fishing season was reduced to a single 24-hour mad dash; given that fish are perishable, this temporal clumping of the catch is not a desirable outcome.



Figure 16.5.2 Marine Fisheries: Fishing Boats. Alaskan waters have been fished by people for thousands of years, but they are under pressure from modern fishing technologies and large-scale extraction. *Source: National Oceanic and Atmospheric Administration*

Resource economists developed the idea of a tradable permit scheme to help manage fisheries. Individual tradable quota (ITQ) schemes are cap-and-trade policies for fish, where total catch is limited but fishers in the fishery are given permits that guarantee them a right to a share of that catch. Players in the fishery can sell their quota shares to each other (helping the catch to flow voluntarily to the most efficient boats in the industry) and there is no incentive for captains to buy excessively large boats or fish too rapidly to beat the other boats to the catch. ITQ policies have rationalized the Alaskan halibut fishery completely: the fish stock is thriving, overcapitalization is gone, and the fish catch is spread out over time (Levy, 2010). ITQs have also been implemented in the fisheries of New Zealand, yielding large improvements in the biological status of the stocks (Annala, 1996). There is some general evidence that ITQ systems have been relatively successful in improving fishery outcomes (Costello, Gaines, & Lynham et al. 2008), though other research implies that evidence of the superiority of the ITQ approach is more mixed (Beddington 2007) Scholars and fishery managers continue to work to identify the details of ITQ management that make such systems work most effectively, and to identify what needs to be done to promote more widespread adoption of good fishery management policy worldwide.

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16.6: Environmental Valuation

Learning Objectives

After reading this module, students should be able to

- understand why it might be useful to develop estimates of the values of environmental goods in dollar terms.
- know the difference between the two economic measures of value, willingness to pay and willingness to accept.
- be familiar with valuation methods in all three parts of the environmental valuation toolkit: direct, revealed preference, and stated preference methods.
- understand the strengths and weaknesses of those valuation methods.

Use Values

Externality, public good, and common-pool resource problems yield suboptimal levels of environmental quality and excessive rates of resource exploitation. Many factors complicate the process of deciding what to do about these problems. One is that environmental goods are not traded in any marketplace, and hence analysts struggle to identify quantitative measures of their values to society.

Environmental valutaion is controversial. Some environmentalists object to efforts to place dollar values on elements of the environment that might be viewed as priceless. Such values are important, however, for making sure that society does not fail to take the value of nature into account when making policy and investment choices. All U.S. government regulations, for example, are subjected to benefit-cost analyses to make sure that government actions don't inadvertently make society worse off (see Module 8.5). If we do not have dollar values for the environmental benefits of things like clean water and air, then estimates of the benefits of pollution control will be consistently lower than the true social benefits, and government policy will chronically underinvest in efforts to control pollution.

Environmental and natural resource economists have worked for decades to develop valuation methods that can be used to generate reasonable estimates of the dollar values of environmental amenities. Thousands of journal articles have been published in this effort to refine valuation methodology. In the early years of valuation studies, most of the work was focused on generating estimates of the social values of water and air quality. Over time, economists broadened their focus to study how to value a broader range of amenities such as wetland habitat and endangered species.

The United Nations launched an international effort in 2000 called the Millennium Ecosystem Assessment which was to evaluate the current state of earth's ecosystems (and the services that flow from nature to humans) and identify strategies for conservation and sustainable use. Reports from this effort) have helped scientists and policy makers develop a new framework for thinking about how nature has value to humans by providing a wide range of ecosystem services. Since then, a surge of multidisciplinary research has emerged to quantify the physical services provided by the environment and estimate the values to humanity of those services. Economists recognize two broad categories of environmental values: use and non-use. Use values flow from services that affect people directly, such as food production, flood regulation, recreation opportunities, and potable water provision. Non-use values are less tangible: the desire for endangered tigers to continue to exist even on the part of people who will never see them in the wild; concern about bequeathing future generations a planet with healthy fish populations; a sense that people have an ethical responsibility to be good stewards of the earth. Economic valuation methods exist to capture all of these environmental values.



Figure 16.6.1 Use Value: Recreational Angler. A fisherman takes advantage of the use value of the natural environment of Four Springs Lake, Tasmania. *Source: Photo by Peripitus*



Figure 16.6.2 Non-use Value: Sumatran Tiger. Although wild tigers do not directly impact people living in the United States, many Americans wish for the species to continue existing in their natural environment. This is an example of a non-use value. *Source: Photo by Nevit Dilman*

Willingness to Pay/Accept

Economists use measures of value that are anthropocentric, or human centered. A rigorous body of theory about consumer choice lies beneath those measures. Mathematical complexity can make that theory seem like unreliable trickery, but in truth, consumer theory rests on only a very small number of fundamental assumptions:

- People have preferences over things.
- People are able to rank any two bundles of goods to identify which one they prefer.
- People are rational in that they will choose the bundle they prefer (over bundles they do not prefer) if they can afford it.

Those uncontroversial axioms are actually enough to derive all the results economists use when working with valuation methodology. However, the derivations are easier and sometimes more intuitive with a little more structure added to our hypothetical consumer choice problem:

- People face budget constraints (total expenditures can’t exceed their income).

- People make choices to make themselves as well off as possible ("maximize their utility") within the rationing forced by their budget constraints.

This framework yields two ways to think about the values of changes to the quality or quantity of environmental goods. Consider first a situation where we are trying to determine the value of a project that yields an environmental improvement—say, for example, water in the Chicago River will be cleaner. The social benefit of that project turns out to be what people are willing to pay for it. The second measure of value is appropriate if we want to measure the value of environmental goods that will be lost or degraded by a deleterious change—say, for example, climate change leading to the extinction of polar bears. In that context, the value of the change is given by the amount of money you would have to pay people in order to make them willing to accept it.

"Willingness to pay" (WTP) is a budget-constrained measure of a change in welfare; a person cannot be willing to pay more money for a change than they have income. In contrast, "willingness to accept" (WTA) is not a budget constrained measure of value—you might have to increase a person's income many times over in order to fully compensate them for the loss of an environmental amenity they hold dear—and can theoretically approach infinity. Empirical studies tend to find that WTA value estimates are larger than equivalent estimates of WTP.

Analysts usually choose whether to use WTA or WTP approaches as a function of the context of the analysis. The "right" measure to use may depend on whether you want value estimates to inform a policy that would improve conditions relative to the current legal status quo, or to understand the consequences of a change that would cause deterioration of some environmental good citizens currently enjoy. Another factor in choosing a valuation method is that WTP is budget constrained while WTA is not. WTP estimates of value tend to be lower in places where people have lower incomes. That variation captures a realistic pattern in the size of willingness to pay for environmental improvements. However, equity problems clearly plague a study that concludes, for example, that improvements in air quality are more valuable to society if they happen in rich areas rather than poor.

All valuation methodologies—WTP and WTA—are designed to estimate values of fairly small changes in the environment, and those values are often setting-specific. Careful analysts can do benefit transfer studies in which they use the results of one valuation study to inform value estimates in a different place. However, such applications must be carried out carefully. The value of a unit change in a measure of environmental integrity is not an immutable constant, and the values of very large changes in either quantity or quality of an environmental amenity usually cannot be estimated. A cautionary example is an influential but widely criticized paper published in *Nature* by Robert Costanza and colleagues that carried out sweeping benefit transfer estimates of the total social values of a number of Earth's biomes (open oceans, forests, wetlands, etc.). The resulting estimates were too large to be correct estimates of WTP because they exceeded the value of the whole world's GDP, and too small to be correct estimates of WTA because life on earth would cease to exist if oceans disappeared, so WTA for that change should be infinity (Costanza et al., 1997).

An Economist's Environmental Valuation Toolkit: Direct, Revealed Preference, and Stated Preference Methods

Early work on environmental valuation estimated the benefits of improved environmental quality using direct methods that exploit easily obtained information about the monetary damage costs of pollution. These methods are still sometimes used (most often by people who are not environmental economists) because of their simple intuitive appeal. An analyst can measure costs associated with pollution; the benefits of environmental cleanup are then the reductions in those costs. Following are some examples:

- *Production damage measures*: Pollution has a deleterious effect on many production processes. For example, air pollution lowers corn yields, thus increasing the cost of producing a bushel of corn. An analyst could try to measure the benefits of eliminating air pollution by calculating the increase in net social benefits that would flow from the corn market as a result of higher yields.
- *Avoided cost measures*: Environmental degradation often forces people to spend money on efforts to mitigate the harm caused by that degradation. One benefit of reversing the degradation is not having to spend that money on mitigation—the avoided cost. For example, hydrological disruption from impervious surfaces in urban areas forces cities to spend money on expensive storm sewer infrastructure to try to reduce floods. A benefit of installing rain gardens and green roofs to manage stormwater might be avoided storm sewer infrastructure costs.
- *Health cost measures*: Pollution has adverse effects on human health. For example, toxic chemicals can cause cancer, and ground level ozone causes asthma. Some measures of the damages caused by pollution simply count the financial costs of such

illnesses, including the costs of cancer treatment and lost wages from adults missing work during asthma attacks.

These measures seem appealing, but are in fact deeply problematic. One of the most serious problems with direct measures is that they often yield woefully incomplete estimates of the benefits of environmental cleanup. Consider the example of cancer above. Suppose a woman gets cancer from drinking contaminated well water. By the time her illness is diagnosed, the cancer is so advanced that doctors can do little to treat her, and she dies a few months later. The medical expenditures associated with this illness are not very large; she and her family would surely have been willing to pay much more money to have eliminated the toxins so she did not ever get sick. The direct health cost measure of the benefits of cleaning up the contaminated water is a serious underestimate of the true benefit to society of that environmental improvement.

A second set of valuation tools called revealed preference methods work to estimate WTP for environmental amenities and quality by exploiting data on actual behaviors and market choices that are related to the environmental good in question. People reveal their WTP for environmental goods with their actions. Three examples of such methods are below.

- *Hedonic price analysis*: We often cannot observe individuals taking direct action to change the quality of the environment to which they are exposed in a given location because they simply cannot effect such change; no one person, for example, can reduce the concentration of fine particles in the air near his house. We do, however, observe market data about the choices people make about where to live. If two houses are otherwise identical but one house is situated in a place with much cleaner air than the other, the benefit of breathing cleaner air will get capitalized in the value of that house. All else equal, neighborhoods with better environments will have more expensive homes. Analysts can gather data on housing prices and house characteristics (both environmental and nonenvironmental) and use a statistical analysis to estimate marginal WTP for elements of environmental quality that vary among the houses in the data set. The hedonic price analysis approach has been used to value amenities such as air quality, hazardous waste site cleanup, and open space.
- *Hedonic wage analysis*: Some forms of pollution cause people to face higher risk of death in any given year. Thus, one important goal of valuation is to estimate a dollar value of reduced mortality resulting from pollution cleanup. Except in the movies, we rarely observe people choosing how much money they are willing to pay to save a specific person from certain death. However, all of us make choices every day that affect our risk of death. One important choice is which job to accept. Elementary school teachers face little job-related mortality risk. In contrast, coal miners, offshore oil rig workers, and deep sea fishermen accept high rates of accidental death when they take their jobs. By analyzing data on wage rates and worker death rates in a variety of different industries, we can estimate WTP to reduce the risk of death. Using such hedonic wage analysis, economists have developed measures of the value of a statistical life(VSL), which can be applied to physical estimates of reductions in pollution-related deaths to find the benefits of reduced mortality.
- *Travel cost analysis*: Many natural amenities, such as forests, lakes, and parks are enjoyed by the public free of charge. While there is no formal market for “hours of quality outdoor recreation,” people do incur costs associated with such recreation—gas purchased to drive to the site, hotel expenses for overnight trips, and the opportunity cost of the time spent on the trip. If environmental quality is valued, people will be willing to pay higher travel costs to visit recreation sites with higher levels of environmental quality (e.g., cleaner water in the lake, more fish to catch, a better view from a mountain with low air pollution). In travel cost analysis, researchers gather data on the environmental features of a set of recreation sites and the choices people make about visiting those sites—which they choose to visit, and how often—and apply statistical analysis to those data to estimate WTP for improved quality of natural amenities.

One of the greatest strengths of revealed preference valuation methods is that they use information about real behavior rather than hypothetical choices. These approaches also yield estimates of WTP that are often more complete than the results of direct market measure studies.

Revealed preference studies do, however, have weaknesses and limitations. First, they only give good estimates of WTP for environmental goods if people have full and accurate information about environmental quality and associated risks. For example, hedonic estimates of WTP to avoid living with polluted air will be biased downward if people in a city do not know how air pollution varies among neighborhoods. Second, some revealed preference approaches are only valid if the relevant markets (labor markets for a wage study, housing markets for a hedonic price study) are not plagued by market power and transaction costs that prevent efficient equilibria from being reached. For example, if workers find it too daunting and costly to move from one region to another, then coal miners may fail to earn the wage premium that would be associated with such a risky job in the absence of

relocation hurdles. Third, revealed preference approaches cannot be used to estimate values for levels of environmental quality that are not observed in real-world data. If all the lakes in a region are terribly polluted, we cannot use a travel cost study of lake site choice to identify WTP for very clean lakes. Fourth, revealed preference methods can capture only use values, not non-use values.

The limitations of revealed preference valuation tools motivated environmental and natural resource economists to develop valuation methods that do not require analysts to be able to observe real-world behavior related to the amenity being valued. These stated preference methods are now highly refined, but the essential idea is simple. These studies design a survey that presents people with information about hypothetical scenarios involving an environmental good, gather data on their responses to questions about how much they would pay for something or whether they would choose one scenario over another, and then analyze the data to estimate WTP for the good or WTA compensation for elimination or degradation of the good.

- *Contingent valuation*: The methodology called contingent valuation (or CV) gained prominent attention when it was used by economists to estimate the damage done to society by the oil spilled by Exxon's *Valdez* oil tanker in Prince William Sound in 1989 (Carson et al., 2003). A CV survey gives a clear description of a single environmental amenity to be valued, such as a wetland restoration, whale populations, or improved water quality in a local lake. The description includes details about how the amenity would be created, and how the survey respondent would pay any money they claim to be willing to pay in support of the amenity. Respondents are then asked a question to elicit their WTP. This value elicitation question can be open ended ("How much would you be willing to pay in taxes to increase whale populations?) or closed ended ("Would you be willing to pay $30 to increase whale populations?). The resulting data set is analyzed to find the average WTP of people in the sample population.
- *Conjoint analysis*: Conjoint analysis is also referred to as choice experiment survey analysis. It was developed first by analysts in business marketing and psychology, and only later adopted by economists for environmental valuation. The main difference between conjoint analysis and CV is that CV elicits WTP for an environmental amenity with a single fixed bundle of features, or attributes. Conjoint analysis estimates separate values for each of a set of attributes of a composite environmental amenity. For example, grasslands can vary in bird species diversity, wildflower coverage, and distance from human population centers. A conjoint analysis of grassland ecosystems would construct a set of hypothetical grasslands with varied combinations of attributes (including the cost to the respondent of a chosen grassland). The survey would present respondents with several choice questions; in each choice, the respondent would be asked to pick which of several hypothetical grasslands they would prefer. The resulting data would be analyzed to find how each attribute affects the likelihood that one grassland is preferred over another. This would yield estimates of marginal values for each attribute; those values could then be used to find WTP for composite grasslands with many different combinations of features.

Both CV and conjoint analysis methods can be designed to estimate WTP for improvement or WTA degradation depending on which context is most appropriate for the problem at hand. These stated preference methods have two main strengths. First, they can capture non-use values. Second, their hypothetical nature allows analysts to estimate WTP for improvements out of the range of current experience (or WTA for degradation we have fortunately not yet experienced).

However, stated preferences approaches do have weaknesses and limitations. For example, many economists are uncomfortable using value estimates derived from hypothetical choices, worrying whether consumers would make the same choices regarding payment for public environmental goods if the payments were real. Scholars also worry about whether people give responses to stated preference surveys that are deliberately skewed from their true WTP. Understatements of value could arise to protest a government policy ("Why should I have to pay to clean up the environment when someone else made it dirty in the first place?") or out of a desire to free ride. Finally, the hypothetical nature of stated preference surveys can mean that some respondents are not familiar with the thing being valued, and thus may have trouble giving meaningful responses to the questions. Stated preference surveys must be designed to give respondents enough information without biasing their responses.

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Review Questions

Question:

Why might it be useful to estimate dollar values for features of the environment?

Question:

What are the three types of valuation tools? List at least one strength and one weakness of each.

Glossary

avoided cost
A type of direct method that equates the value of an environmental improvement with a cost that can then be avoided.

benefit transfer
A method for estimating the value of a natural amenity by applying estimates from a complex study of a slightly different (but similar) amenity to the case at hand.

conjoint analysis
A stated preference valuation tool that allows an analyst to estimate the marginal values of multiple attributes of an environmental good.

contingent valuation
A stated preference valuation tool that describes a single environmental good and elicits survey responses from which the analyst can estimate people's value for that good.

direct methods
Valuation tools that use data on actual market transactions to estimate the value of a change in the environment.

ecosystem services
Resources and processes through which the environment gives benefits to humanity.

hedonic price analysis
A revealed preference tool that uses data on house prices and characteristics to estimate the value of features of the environment that vary among houses.

hedonic wage analysis
A revealed preference tool that uses data on wages and risk of death by job type estimate willingness to pay to reduce the risk of death.

non-use values
Values people have for nature that do not stem from direct interaction.

revealed preference
Valuation tools that use behaviors such as job choice, housing choice, and recreational site choice to reveal information about the values people have for features of the environment.

stated preference
Valuation tools that use survey responses to hypothetical questions rather than data on actual choices.

travel cost analysis
A revealed preference tool that estimates the values of natural resource amenities by analyzing data on recreational site characteristics and people's visitation patterns and travel costs.

use values

Benefits associated with direct interaction with nature and the environment.

valuation

The process of estimating a dollar value for an amenity or a disamentity.

value of a statistical life

A statistical concept that can be used as the value of reducing the number of deaths in a population by one.

willingness to accept

The amount of money you would have to pay someone to compensate them for a deleterious change.

willingness to pay

The amount of money someone is willing to pay for something good.

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16.7: The Human Dimensions of Sustainability- History, Culture, Ethics



Figure 16.7.1 Earth day

Once we begin talking about sustainability, it's hard to stop. That's because sustainability is truly the science of everything, from technical strategies for repowering our homes and cars, to the ecological study of biodiversity in forests and oceans, to how we think and act as human beings. This latter category—the "human dimensions" of sustainability—is the focus of this chapter. Much sustainability discourse focuses on scientific, technical and regulatory issues, but there is increasing awareness that without changes in people's attitudes and patterns of behavior, and how these attitudes are reflected in public policymaking priorities, meaningful reform toward a more sustainable management of natural resources will be impossible. One key to this problem is that we are accustomed to thinking of the environment as a remote issue. Even the words "environment" and "nature" themselves suggest the habitual view we take of ourselves as somehow independent of or superior to the planet's material resources and processes. The truth is different. Humanity is but a thread of nature's web, albeit an original and brilliant thread. So brilliant indeed that we are now shaping the evolution of the web itself, to our short-term advantage, but in ways that cannot be sustained.

One example of the centrality of the human dimensions component of sustainability studies is the fact that sustainable technologies of food and energy production are increasingly available, but have yet to be adapted on the necessary scale to make a difference to humanity's overall environmental footprint on the planet. Many look to technology for answers to our myriad environmental problems, but the fact that even the limited technological innovations that exist lack support and have been inadequately deployed is a complex human issue, touching an essential resistance to change in our economic and political structures, our lifestyles and culture and, at the micro-level, basic human psychology and behavior. This chapter will explore these human dimensions of the sustainability challenge, with an emphasis on the historical and cultural factors that have placed us on our dangerously unsustainable path, and which make changing course so challenging.

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.

Glossary

Adaptation

Focuses on the need for strategies to deal with the climate change that is unavoidable because of increased carbon already in the atmosphere

Mitigation

Refers to the importance of reducing carbon emissions so as to prevent further, catastrophic changes in the climate system.

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16.8: It’s Not Easy Being Green- Anti-Environmental Discourse, Behavior, and Ideology

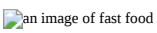
Introduction

The consensus view among scientists and professional elites in the early twenty-first century, as it has been among environmental activists for a much longer time, is that our globalized industrial world system is on an unsustainable path. Inherent in this view is a stern judgment of the recent past: we have not adapted well, as a species, to the fruits of our own brilliant technological accomplishments, in particular, to the harnessing of fossil fuels to power transport and industry.

Taking the long view of human evolution, it is not surprising to find that we are imperfectly adapted to our modern industrialized world of cars, computers, and teeming cities, or that human societies organized for so many millennia around the problem of scarcity should treat a sudden abundance of resources with the glee of a kid in a candy store. In evolutionary terms, we have simply not had sufficient time to adapt to the windfall of change. Though rapid advances in the biophysical sciences in recent decades mean that we mostly understandour maladaptation to industrialization and the great dangers it poses, our political decision-making and consumption patterns have barely changed on the basis of this understanding. This sobering fact tells us that, at this moment in human history, social behavior and political decision-making are not being driven by knowledge, but rather by entrenched attitudes that perpetuate an unsustainable drawdown of earth’s resources. In short, human decision making and consumption of material goods in our fossil-fuel age continues to largely take place outside of an awareness of the strained and finite nature of our planet’s ecosystem services.

It is the character of modern consumer society to promote the idea that nothing is connected, that the jeans we wear, or the food we eat, are matters of personal choice without any greater context beyond a concern for immediate pleasure and peer approval. Sustainability, by contrast, teaches that everything is connected. That favorite pair of jeans, for instance, is dependent on cheap labor in developing countries, on heavily fertilized cotton plantations, and enormous volumes of water expended throughout the jeans’ lifecycle, from the irrigation to grow the cotton to the washing machine that cleans them. Or let’s take that “cheap” fast food lunch from yesterday: it most likely contained processed soybeans from a recently cleared stretch of the Amazon rainforest, and artificial sweeteners made from corn whose enormous production quotas are subsidized by government tax revenues. The corn-based sweetener, in turn, turns out to be a principal cause of the national obesity epidemic, a key contributor to spiraling health care costs. Thus the “value meal” turns out not to be so economical after all, once the systems-wide effects are factored in.

A twenty minute video, The Story of Stuff, tells the complicated story of how our "stuff" moves from extraction to sale to disposal.


an image of fast food Figure 16.8.2 Fast Food Industry's Environmental Impact? Here’s food for thought. Though we are accustomed to measuring the impact of a fast food diet on our physical health, there is much less readily available information on the global network of agricultural providers that supports the fast food industry, and on its environmental impacts on land use, water resources, and human communities. Source: Created by CrazyRob926

Connectivity

To think about sustainability in these terms may sound exhausting. But because we live in a world characterized by connectivity, that is, bycomplex chains linking our everyday lives to distant strangers and ecosystems in far flung regions of the earth, we have no choice. In the end, we must adapt our thinking to a complex, connected model of the world and our place in it. Persisting with only simple, consumerist frames of understanding—“I look great!” “This tastes delicious!”—for a complex world of remote impacts and finite resources renders us increasingly vulnerable to episodes of what ecologists call system collapse, that is, to the sudden breakdown of ecosystem services we rely upon for our life’s staple provisions.

In the early twenty-first century, vulnerability to these system collapses varies greatly according to where one lives. A long-term drought in India might bring the reality of aquifer depletion or climate change home to tens of thousands of people driven from their land, while the life of a suburban American teenager is not obviously affected by any resource crisis. But this gap will narrow in the coming years. Overwhelming scientific evidence points to rapidly increasing strains this century on our systems of food, water, and energy provision as well as on the seasonable weather to which we have adapted our agricultural and urban regions. In time, no one will enjoy the luxury of remaining oblivious to the challenges of sustainability. Drought, for example, is one of the primary indices of global ecosystem stress, and arguably the most important to humans. According to the United Nations Food and

Agriculture Organization, without wholesale reformation of water management practices on a global scale, two-thirds of the world's population will face water shortages by 2025, including densely populated regions of the United States.

So how did we arrive at this point? Without you or I ever consciously choosing to live unsustainably, how has it nevertheless come about that we face environmental crises of global scale, circumstances that will so decisively shape our lives and those of our children? Here's one explanatory narrative, framed by the long view of human evolution.

Since the emergence of the first proto-human communities in Africa millions of years ago, we have spent over 99% of evolutionary time as nomadic hunters and gatherers. A fraction of the balance of our time on earth spans the 10,000 years of human agriculture, since the end of the last Ice Age. In turn, only a third of that fractional period has witnessed the emergence of the institutions and technologies—writing, money, mathematics, etc.—that we associate with human "civilization." And lastly, at the very tip of the evolutionary timeline, no more than a blink of human species history, we find the development of the modern industrialized society we inhabit. Look around you. Observe for a moment all that is familiar in your immediate surroundings: the streetscape and buildings visible through the window, the plastic furnishings in the room, and the blinking gadgets within arm's length of where you sit. All of it is profoundly "new" to human beings; to all but a handful of the tens of thousands of generations of human beings that have preceded us, this everyday scene would appear baffling and frightening, as if from another planet.

Normalization

In this sense, the real miracle of human evolution is that cars, computers, and cities appear so normal to us, even sometimes "boring" and monotonous! Our perception of the extraordinary, rapid changes in human societies in the past two centuries—even the past half-century—is deadened by virtue of what is our greatest evolutionary acquirement, namely normalization, an adaptive survival strategy fundamental to human success over the millennia. The ability to accept, analyze, and adapt to often fluctuating circumstances is our great strength as a species. But at this point in human history it is also a grave weakness, what, in the language of Greek tragedy might be called a "fatal flaw."

To offer an analogy, for many centuries slavery appeared normal to most people across the world—until the late eighteenth century, when a handful of humanitarian activists in Britain began the long and difficult process of de-normalizing human bondage in the eyes of their compatriots. The task of sustainability ethics is analogous, and no less difficult, in that it lays out the argument for wholesale and disruptive attitude adjustment and behavior change in the general population. Given the long-term adaptation of the human species to the imperatives of hunter-gathering, our decision-making priorities and consumption drives still tend toward the simple necessities, based on the presumption of relative and seasonal scarcity, and with little emotional or social reward for restraint in the face of plenty, for viewing our choices in global terms, or for measuring their impacts on future generations.

A working distinction between the historical evolution of human *society* and human *culture* is useful to understanding the social and psychological obstacles to achieving sustainability. As both individuals and societies, we work hard to insulate ourselves from unpleasant surprises, shocks, and disorder. We crave "security," and our legal and economic institutions accordingly have evolved over the millennia to form a buffer against what Shakespeare's Hamlet called "the thousand natural shocks that flesh is heir to." For instance, the law protects us from violent physical harm (ideally), while insurance policies safeguard us from financial ruin in the event of an unexpected calamity.

In one sense, this security priority has determined the basic evolution of human societies, particularly the decisive transition 10,000 years ago from the variable and risky life of nomadic hunter communities to sedentary farming based on an anticipated stability of seasonal yields. Of course, the shift to agriculture only partially satisfied the human desire for security as farming communities remained vulnerable to changing climatic conditions and territorial warfare. Global industrialization, however, while it has rendered vast populations marginal and vulnerable, has offered its beneficiaries the most secure insulation yet enjoyed by humans against "the slings and arrows of outrageous fortune." This success has been a double-edged sword, however, not least because the industrialized cocoon of our modern consumer lifestyles relentlessly promotes the notion that we have transcended our dependence on the earth's basic resources. As it stands, we look at our highly complex, industrialized world, and adapt our expectations and desires to its rewards. It is never our first instinct to ask whether the system of rewards itself might be unsustainable and collapse at some future time as a result of our eager participation.

Sustainability Obstacles and Support

In terms of the evolutionary argument I am outlining here, our ability to grasp the sustainability imperative faces two serious obstacles. The first is psychological, namely the inherited mental frameworks that reward us for the normalization and simplification of complex realities. The second is social, namely our economic and institutional arrangements designed to protect us from material wants, as well as from risk, shock, disorder and violent change. Both these psychological and social features of our lives militate against an ecological, systems-based worldview.

Luckily, our *cultural* institutions have evolved to offer a counterweight to the complacency and inertia encouraged by the other simple, security-focused principles governing our lives. If society is founded upon the principle of security, and promotes our complacent feeling of independence from the natural world, we might think of culture as the conscience of society. What culture does, particularly in the arts and sciences, is remind us of our frailty as human beings, our vulnerability to shocks and sudden changes, and our connectedness to the earth's natural systems. In this sense, the arts and sciences, though we conventionally view them as opposites, in fact perform the same social function: they remind us of what lies beyond the dominant security paradigm of our societies—which tends to a simplified and binary view of human being and nature—by bringing us closer to a complex, systemic understanding of how the natural world works and our embeddedness within it. Whether by means of an essay on plant biology, or a stage play about family breakdown (like *Hamlet*), the arts and sciences model complex worlds and the systemic interrelations that shape our lives. They expose complexities and connectivities in our world, and emphasize the material consequences of our actions to which we might otherwise remain oblivious. The close relation between the arts and sciences in the Western world is evidenced by the fact that their concerns have largely mirrored each other over time, from the ordered, hierarchical worldview in the classical and early modern periods, to the post-modern focus on connectivity, chaos, and emergence.

Life in the pre-modern world, in the memorable words of the English philosopher Thomas Hobbes, was mostly "nasty, brutish, and short." By contrast, social and economic evolution has bestowed the inhabitants of the twenty-first century industrialized world with a lifestyle uniquely (though of course not wholly) insulated from physical hardship, infectious disease, and chronic violence. This insulation has come at a cost, however, namely our disconnection from the basic support systems of life: food, water and energy. This is a very recent development. At the beginning of the 20th century, for example, almost half of Americans grew up on farms. Now, fewer than two percent do. We experience the staples of life only at their service endpoints: the supermarket, the faucet, the gas station. In this context, the real-world sources of food, water, and energy do not seem important, while supplies appear limitless. We are not prepared for the inevitable shortages of the future.

On the positive side, it is possible to imagine that the citizens of the developed world might rapidly reconnect to a systems view of natural resources. One product of our long species evolution as hunters and agricultural land managers is an adaptive trait the ecologist E. O. Wilson has called "biophilia," that is, a love for the natural world that provides for us. In the few centuries of our fossil fuel modernity, this biophilia has become increasingly aestheticized and commodified—as landscape art, or nature tourism—and consequently marginalized from core social and economic decision structures. In the emerging age of environmental decline and resource scarcity, however, our inherited biophilia will play a key role in energizing the reform of industrialized societies toward a sustainable, renewable resource and energy future.

Review Questions

1. How has the human capacity for *normalization* both helped and hindered social development, and what are its implications for sustainable reform of our industries, infrastructure, and way of life?
2. Take an everyday consumer item—running shoes, or a cup of coffee—and briefly chart its course through the global consumer economy from the production of its materials to its disposal. What are its environmental impacts, and how might they be reduced?

Glossary

Connectivity

An important feature of complex systems. Connections exist between even apparently remote and disparate things. For example, drought in Australia might impact the price of bread in Egypt, which in turn has repercussions for U.S. foreign policy.

Normalization

An acquired evolutionary trait characteristic of human beings, whereby even radical changes are quickly adapted to and represented as normal.

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