ENVIRONMENTAL SCIENCE

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Environmental Science

Melissa Ha and Rachel Schleiger

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UNIT 1: INTRODUCTION

The objective of this unit is to not only get you acquainted with what this book will cover but to also introduce the rigors and structure of science and how mathematics plays a crucial role in helping scientists interpret results in the most unbiased way possible. Science and mathematics are not just for scientists. A base understanding of these subjects is crucial in our very complex modern world. Without a solid understanding of how science and mathematics play a role in our everyday lives, we cannot respond appropriately in everyday situations, know how to vote on scientific laws, or hold public representatives responsible for their decisions on scientific policy.

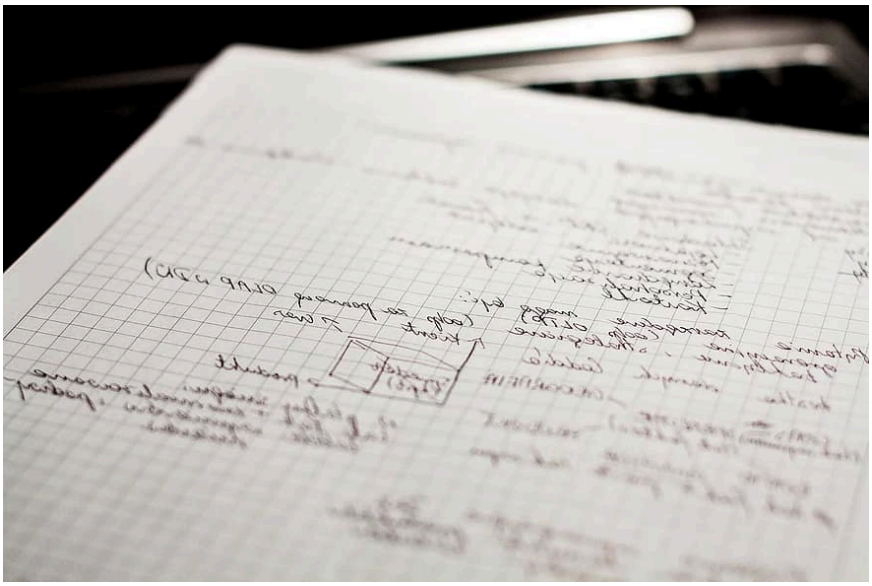

Figure $1.a$ Written notes. Image by Pikist (Public domain)

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1: Environmental Science Preface

What is Environmental Science?

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

Environmental Science is Interdisciplinary

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

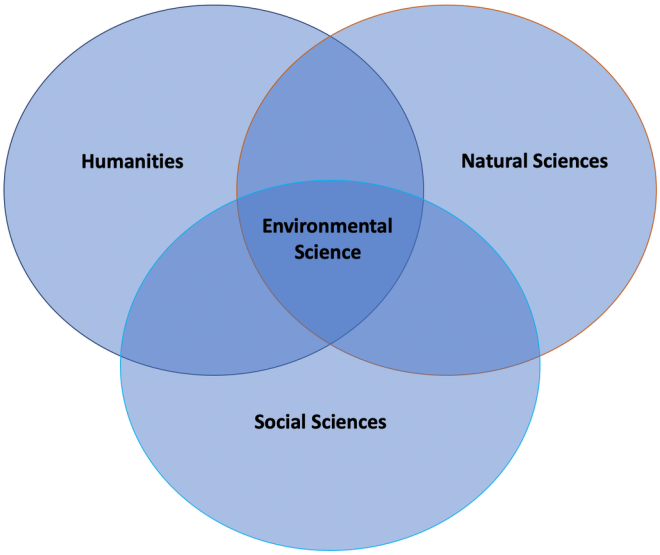

Figure $1.a$: Venn diagram illustrating how environmental science is interdisciplinary between humanities, natural sciences (which includes physical and life sciences) and social sciences. Image by Rachel Schleiger (CC-BY-NC).

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.

The Tragedy of the Commons

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

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

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

Some Indicators of Global Environmental Stress

- **Forests** — Deforestation remains a main issue. 1 million hectares of forest were lost every year in the decade 1980-1990. The largest losses of forest area are taking place in the tropical moist deciduous forests, the zone best suited to human settlement and agriculture. Recent estimates suggest that nearly two-thirds of tropical deforestation is due to farmers clearing land for agriculture. There is increasing concern about the decline in forest quality associated with intensive use of forests and unregulated access.
- **Soil** — As much as 10% of the earth's vegetated surface is now at least moderately degraded. Trends in soil quality and management of irrigated land raise serious questions about longer-term sustainability. It is estimated that about 20% of the world's 250 million hectares of irrigated land are already degraded to the point where crop production is seriously reduced.
- **Fresh water** — Some 20% of the world's population lacks access to safe water and 50% lacks access to safe sanitation. If current trends in water use persist, two-thirds of the world's population could be living in countries experiencing moderate or high water stress by 2025.
- **Marine fisheries** — 25% of the world's marine fisheries are being fished at their maximum level of productivity and 35% are overfished (yields are declining). In order to maintain current per capita consumption of fish, global fish harvests must be increased; much of the increase might come through aquaculture which is a known source of water pollution, wetland loss and mangrove swamp destruction.
- **Biodiversity** — Biodiversity is increasingly coming under threat from development, which destroys or degrades natural habitats, and from pollution from a variety of sources. The first comprehensive global assessment of biodiversity put the total number of species at close to 14 million and found that between 1% and 11% of the world's species may be threatened by extinction every decade. Coastal ecosystems, which host a very large proportion of marine species, are at great risk with perhaps one-third of the world's coasts at high potential risk of degradation and another 17% at moderate risk.
- **Atmosphere** — The Intergovernmental Panel on Climate Change has established that human activities are having a discernible influence on global climate. CO_2 emissions in most industrialized countries have risen during the past few years and countries generally failed to stabilize their greenhouse gas emissions at 1990 levels by 2000 as required by the Climate Change convention.
- **Toxic chemicals** — About 100,000 chemicals are now in commercial use and their potential impacts on human health and ecological function represent largely unknown risks. Persistent organic pollutants are now so widely distributed by air and ocean currents that they are found in the tissues of people and wildlife everywhere; they are of particular concern because of their high levels of toxicity and persistence in the environment.
- **Hazardous wastes** — Pollution from heavy metals, especially from their use in industry and mining, is also creating serious health consequences in many parts of the world. Incidents and accidents involving uncontrolled radioactive sources continue to increase, and particular risks are posed by the legacy of contaminated areas left from military activities involving nuclear materials.
- **Waste** — Domestic and industrial waste production continues to increase in both absolute and per capita terms, worldwide. In the developed world, per capita waste generation has increased threefold over the past 20 years; in developing countries,

it is highly likely that waste generation will double during the next decade. The level of awareness regarding the health and environmental impacts of inadequate waste disposal remains rather poor; poor sanitation and waste management infrastructure is still one of the principal causes of death and disability for the urban poor.

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2: WHAT IS SCIENCE, AND HOW DOES IT WORK?

Chapter Hook

It's 1935, and you have another sore throat, the second time this month. After a doctor appointment you are referred to an otolaryngologist (ear, nose, and throat doctor). After a short appointment you are scheduled for a tonsillectomy the next day. The majority of children during this time period had their tonsils removed. In fact, the history of tonsillectomies goes back 2000 years! Medical professionals knew that taking out tonsils had benefits for their patients, mainly decreased throat infections and improved sleep due to obstructive sleep apnea. However, there was not extensive research performed on long term risks in addition to the surgical risks. By the 1970s tonsillectomy recommendations significantly decreased after research confirmed long term side effects for some patients. This is one of many examples where procedures and policies were created without appropriate evidence utilizing the scientific method, the backbone of science.

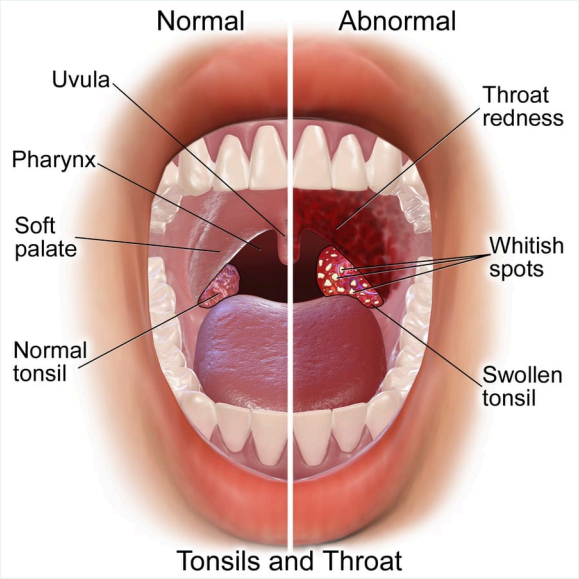

Figure $2.a$ Anatomy of normal versus abnormal tonsils and throat. Image by BruceBlaus (licensed under CC-BY-3.0)

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2.1: What is Science?

Like other natural sciences, environmental science gathers knowledge about the natural world. Science is more than just a body of knowledge, science provides a means to evaluate and create new knowledge. 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 $2.1.a$). 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.

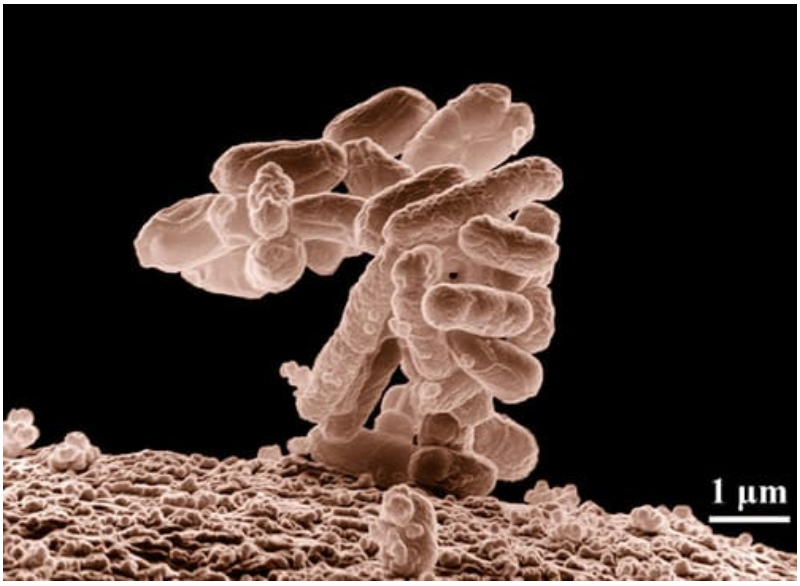

Figure $2.1.a$: Biologists may choose to study *Escherichia coli* (*E. coli*), a bacterium that is a normal resident of our digestive tracts but which is also sometimes responsible for disease outbreaks. In this micrograph, the bacterium is visualized using a scanning electron microscope and digital colorization. (credit: Eric Erbe; digital colorization by Christopher Pooley, USDA-ARS)

There are areas of knowledge, however, to which the methods of science cannot be applied. 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.

Evidence, Measurements, and Observations

Scientists use objective evidence over subjective evidence, to reach sound and logical conclusions. An **objective** observation is without personal bias and the same by all individuals. **Bias** refers to favoring one thing over another, and it can lead to inaccurate results. Humans are biased by nature, so they cannot be completely objective; the goal is to be as unbiased as possible. A **subjective** observation is based on a person's feelings and beliefs and is unique to that individual (figure $2.1.b$).

Figure $2.1.b$: This is Grand Canyon of the Yellowstone in Yellowstone National Park. An objective statement about this would be, “The picture is of a waterfall.” A subjective statement would be, “The picture is beautiful.”

Another way scientists avoid bias is by using quantitative over qualitative measurements whenever possible. A **quantitative measurement** is expressed with a specific numerical value. **Qualitative observations** are general or relative descriptions. For example, describing a rock as red or heavy is a qualitative observation. Determining a rock’s color by measuring wavelengths of reflected light or its density by measuring the proportions of minerals it contains is quantitative. Numerical values are more precise than general descriptions, and they can be analyzed using statistical calculations. This is why quantitative measurements are much more useful to scientists than qualitative observations.

Inductive and Deductive Reasoning

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. 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. Surveying land use (which areas are forested, agricultural, urban, etc.) across the United States and then concluding that forested areas are concentrated in the West is an example of descriptive 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. Deductive reasoning, or deduction, is the type of logic used in hypothesis-based science (see below).

To summarize, inductive reasoning moves from the specific (an observation) to general (conclusion), and deductive reasoning moves from the general (a hypothesis or principle) to the specific (results).

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.

Science is also a Social Process

Scientists share their ideas with peers at conferences, seeking guidance and feedback (figure $2.1.c$). Research papers and data submitted for publication are rigorously reviewed by qualified peers, scientists who are experts in the same field. The scientific review process aims to weed out misinformation, invalid research results, and wild speculation. Thus, it is slow, cautious, and conservative. Scientists tend to wait until a hypothesis is supported by an overwhelming amount of evidence from many independent researchers before accepting it as a **scientific theory**.

Figure $2.1.c$: Scientists share information by publishing and attending conferences. The conference shown here focuses on peanut and mycotoxin (harmful chemicals produced by fungi) research. Image by Sharon Dowdy (CC-BY-NC).

Characteristics of Scientists

There is nothing mysterious or even particularly unusual about the things that scientists do. There are many ways to work on scientific problems. They all require common sense. Beyond that, they all display certain features that are especially - but not uniquely - characteristic of science.

- Skepticism — Good scientists use highly-critical standards in the judging of evidence. They approach data, claims, and theories (ideally, even their own!) with healthy doses of skepticism.
- Tolerance of uncertainty — Scientists often work for years - sometimes for an entire career - trying to understand one scientific problem. This often involves finding facts that, for a time, fail to fit into any coherent pattern and that even may support mutually contradictory explanations. Sometimes, as one listens to scientists vigorously defending their views, their confidence seems absolute. But deep in their hearts, they know that their views are based on probabilities and that a new piece of evidence may turn up at any time and force a major shift in their views.
- Although they certainly have no monopoly on hard work, their willingness to work long hours and years pursuing a problem is the mark of all good scientists. For science is hard work.

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2.2: The Scientific Method

The **scientific method** is a process of research with defined steps that include data collection and careful observation.

Observation

Scientific advances begin with **observations**. This involves noticing a pattern, either directly or indirectly from the literature. An example of a direct observation is noticing that there have been a lot of toads in your yard ever since you turned on the sprinklers, where as an indirect observation would be reading a scientific study reporting high densities of toads in urban areas with watered lawns.

During the Vietnam War (figure $2.2.a$), press reports from North Vietnam documented an increasing rate of birth defects. While this credibility of this information was initially questioned by the U.S., it evoked questions about what could be causing these birth defects. Furthermore, increased incidence of certain cancers and other diseases later emerged in Vietnam veterans who had returned to the U.S. This leads us to the next step of the scientific method, the question.

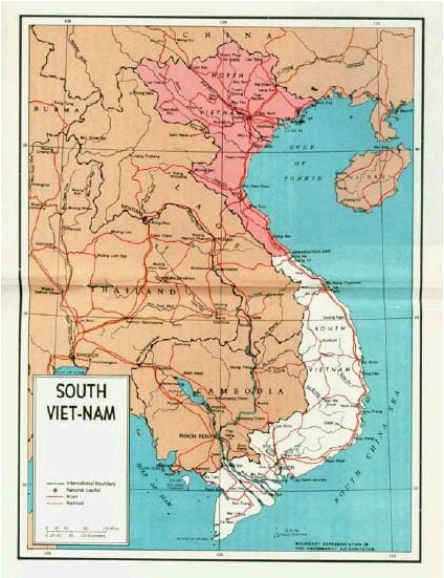

Figure $2.2.a$: A map of Vietnam 1954-1975. Image from Bureau of Public Affairs U.S. Government Printing Office (public domain).

Question

The **question** step of the scientific method is simply asking, what explains the observed pattern? Multiple questions can stem from a single observation. Scientists and the public began to ask, what is causing the birth defects in Vietnam and diseases in Vietnam veterans? Could it be associated with the widespread military use of the herbicide Agent Orange to clear the forests (figure $2.2.b - c$), which helped identify enemies more easily?

Figure $2.2.b$: Agent Orange drums in Vietnam. Image by U.S. Government (public domain).

Figure $2.2.c$: A healthy mangrove forest (top), and another forest after application of Agent Orange. Image by unknown author (public domain).

Hypothesis and Prediction

The **hypothesis** is the expected answer to the question. The best hypotheses state the proposed direction of the effect (increases, decreases, etc.) and explain why the hypothesis could be true.

- OK hypothesis: Agent Orange influences rates of birth defects and disease.
- Better hypothesis: Agent Orange increases the incidence of birth defects and disease.
- Best hypothesis: Agent Orange increases the incidence of birth defects and disease because these health problems have been frequently reported by individuals exposed to this herbicide.

If two or more hypotheses meet this standard, the simpler one is preferred.

Predictions stem from the hypothesis. The prediction explains what results would support hypothesis. The prediction is more specific than the hypothesis because it references the details of the experiment. For example, "If Agent Orange causes health problems, then mice experimentally exposed to TCDD, a contaminant of Agent Orange, during development will have more frequent birth defects than control mice" (figure $2.2.d$).

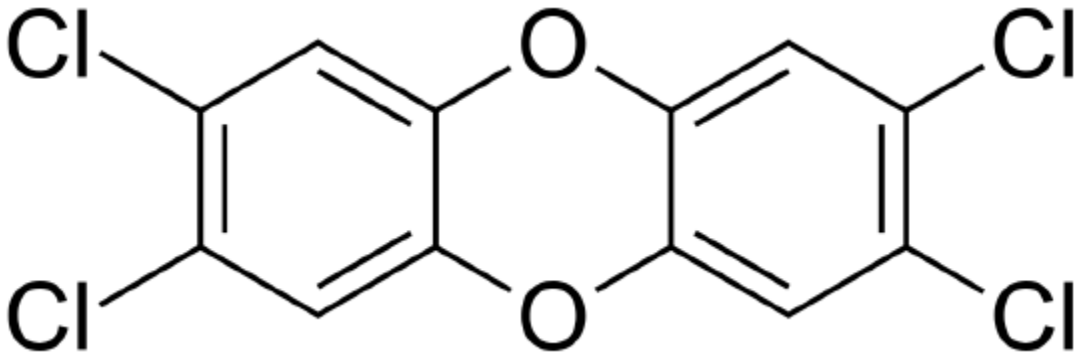

Figure $2.2.d$: The chemical structure of TCDD (2,3,7,8-tetrachlorodibenzo-p-dioxin), which is produced when synthesizing the chemicals in Agent Orange. It contaminates Agent Orange at low but harmful concentrations. Image by Emeldir (public domain).

Hypotheses and predictions 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 they have the capacity to be tested and demonstrated to be untrue. 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.

Hypotheses are tentative explanations and are different from scientific theories. 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.

Design an Experiment

Next, a scientific study (experiment) is planned to test the hypothesis and determine whether the results match the predictions. Each experiment will have one or more variables. The **independent variable** is what scientists hypothesize might be causing something else. In a manipulative experiment (see below), the independent variable is manipulated by the scientist. The **dependent variable** is the response, the variable ultimately measured in the study. **Controlled variables** (confounding factors) might affect the dependent variable, but they are not the focus of the study. Scientist attempt to standardize the controlled variables so that they do not influence the results. In our previous example, exposure to Agent Orange is the independent variable. It is hypothesized to cause a change in health (likelihood of having children with birth defects or developing a disease), the dependent variable. Many other things could affect health, including diet, exercise, and family history. These are the controlled variables.

There are two main types of scientific studies: experimental studies (manipulative experiments) and observational studies.

In a **manipulative experiment**, the independent variable is altered by the scientists, who then observe the response. In other words, the scientists apply a **treatment**. An example would be exposing developing mice to TCDD and comparing the rate of birth defects to a control group. The **control group** is 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, treatment, or **test group**). The purpose of the control group is to establish what the dependent variable would be under normal conditions, in the absence of the experimental treatment. It serves as a baseline to which the test group can be compared. In this example, the control group would contain mice that were not exposed to TCDD but were otherwise handled the same way as the other mice (figure $2.2.e$)

Figure $2.2.e$: Laboratory mice. In a proper scientific study, the treatment would be applied to multiple mice. Another group of mice would not receive the treatment (the control group). Image by Aaron Logan (CC-BY).

In an **observational study**, scientists examine multiple samples with and without the presumed cause. An example would

be monitoring the health of veterans who had varying levels of exposure to Agent Orange.

Scientific studies contain many **replicates.** Multiple samples ensure that any observed pattern is due to the treatment rather than naturally occurring differences between individuals. A scientific study should also be **repeatable**, meaning that if it is conducted again, following the same procedure, it should reproduce the same general results. Additionally, multiple studies will ultimately test the same hypothesis.

Results

Finally, the data are collected and the results are analyzed. As described in the Math Blast chapter, statistics can be used to describe the data and summarize data. They also provide a criterion for deciding whether the pattern in the data is strong enough to support the hypothesis.

The manipulative experiment in our example found that mice exposed to high levels of 2,4,5-T (a component of Agent Orange) or TCDD (a contaminant found in Agent Orange) during development had a cleft palate birth defect more frequently than control mice (figure $2.2.f$). Mice embryos were also more likely to die when exposed to TCDD compared to controls.

Figure $2.2.f$: Cleft lip and palate, a birth defect in which these structures are split. Image by James Heilman, MD (CC-BY-SA).

An observational study found that self-reported exposure to Agent Orange was positively correlated with incidence of multiple diseases in Korean veterans of the Vietnam War, including various cancers, diseases of the cardiovascular and nervous systems, skin diseases, and psychological disorders. Note that a **positive correlation** simply means that the independent and dependent variables both increase or decrease together, but further data, such as the evidence provided by manipulative experiments is needed to document a **cause-and-effect relationship**. (A **negative correlation** occurs when one variable increases as the other decreases.)

Conclusion

Lastly, scientists make a conclusion regarding whether the data support the hypothesis. In the case of Agent Orange, the data, that mice exposed to TCDD and 2,4,5-T had higher frequencies of cleft palate, matches the prediction. Additionally, veterans exposed to Agent Orange had higher rates of certain diseases, further supporting the hypothesis. We can thus accept the hypothesis that Agent Orange increases the incidence of birth defects and disease.

In practice, the scientific method is not as rigid and structured as it might 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 (figure $2.2.g$). Even if the hypothesis was supported, scientists may still continue to test it in different ways. For example, scientists explore the impacts of Agent Orange, examining long-term health impacts as

Vietnam veterans age.

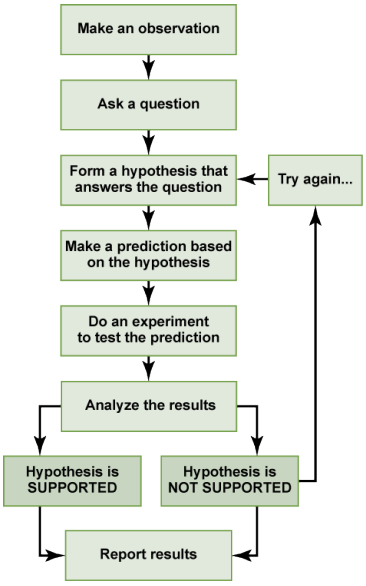

Figure $2.2.g$: The scientific method is a series of defined steps that include experiments and careful observation. The steps are as follows: make an observation; ask a question; form a hypothesis that answers the question; make a prediction based on the hypothesis; do an experiment to test the prediction; analyze the results; and report the results. Whether the hypothesis is supported or not supported, the results are still reported. If a hypothesis is not supported by data, a new hypothesis can be proposed.

Scientific findings can influence decision making. In response to evidence regarding the effect of Agent Orange on human health, compensation is now available for Vietnam veterans who were exposed to Agent Orange and develop certain diseases. The use of Agent Orange is also banned in the U.S. Finally, the U.S. has began cleaning sites in Vietnam that are still contaminated with TCDD.

Building on the Work of Others

Only rarely does a scientific discovery spring full-blown on the scene. When it does, it is likely to create a revolution in the way scientists perceive the world around them and to open up new areas of scientific investigation. Darwin's theory of evolution and Mendel's rules of inheritance are examples of such revolutionary developments. Most science, however, consists of adding another brick to an edifice that has been slowly and painstakingly constructed by prior work.

The development of a new technique often lays the foundation for rapid advances along many different scientific avenues. Just consider the advances in biology that discovery of the light microscope and, later, the electron microscope have made possible. Throughout these pages, there are many examples of experimental procedures. Each was developed to solve a particular problem. However, each was then taken up by workers in other laboratories and applied to their problems.

In a similar way, the creation of a new explanation (hypothesis) in a scientific field often stimulates workers in related fields to reexamine their own field in the light of the new ideas. Darwin's theory of evolution, for example, has had an enormous impact on virtually every subspecialty in biology as well as environmental science. To this very day, scientists in specialties as different as biochemistry and conservation biology are guided in their work by evolutionary theory (figure $2.2.g$).

Figure $2.2.h$: Understanding the endangered mountain yellow-legged frog through the lens of evolution and genetics has aided its conservation. Image by Iasaac Chellman/NPS (CC-BY).

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2.3: Scientific Papers

This section discusses what peer review is and how scientific papers are structured.

Peer Review

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 (figure $2.3.a$). **Peer-reviewed articles** are scientific papers that are evaluated, 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. Peer reviewers assess experimental design, statistical analysis, presentation of data, and whether conclusions fit the results. The process of peer review helps to ensure that the research described in a scientific paper 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.

Figure $2.3.a$: The findings of scientific studies are published in peer-reviewed scientific journals. Image by free svg (public domain).

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).

Structure of Scientific Papers

Scientific papers are usually divided into several sections (not necessarily in this order).

Summary or Abstract

This section includes only the essence of the other sections. It should be as brief as possible, telling the reader what the goal of the experiment was, what was found, and the significance of the findings. The abstract is often placed at the beginning of the paper rather than at its end.

Introduction

This section of the paper describes the scientific question or problem that was the subject of the investigation. The introduction also includes references to earlier reports of these and other scientists that have served as the foundation for the present work. Finally, the introduction states the hypothesis.

Materials and Methods

Here are precisely described the materials used (e.g., strains of organism, source of the reagents) and all the methods followed. The goal of this section is to give all the details necessary for workers in other laboratories to be able to **repeat the experiments exactly**. When many complex procedures are involved, it is acceptable to refer to earlier papers describing these methods in greater detail.

Results

Here the authors report what happened in their experiments. This report is usually supplemented with graphs, tables, and photographs.

Discussion

Here the authors point out what they think is the significance of their findings. This is the place to show that the results are compatible with certain hypotheses and less compatible, or even incompatible, with others. If the results contradict the results of similar experiments in other laboratories, the discrepancies are noted here, and an attempt may be made to reconcile the differences.

Acknowledgments

In this brief but important section, the authors give credit to those who have assisted them in the work. These usually include technicians (who may have actually performed most of the experiments!) and other scientists who donated materials for the experiments and/or gave advice about them.

References

This section gives a careful listing of all earlier scientific work referred to in the main body of the paper. Most of the references are to other scientific papers. Each reference should provide enough information so that another person can locate the document. This means that each reference should include the name(s) of the author(s), the journal or book in which the report appears, and the year of publication. In the case of scientific journals, the volume number in which the paper appears and the page number on which the paper begins should be included. A digital object identifier (DOI) or url is often included. The full title of the article is often included as well, although some citation styles omit the title from the reference.

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2.4: 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. Questions such as, "How have plants evolved to attract pollinators?" and "What factors determine which species will co-occur with each other?" fall under the scope of basic science (figure $2.4.a$).

Figure $2.4.a$: Many different plant species are co-occurring (growing together) at the Brisbane Botanic Gardens. Exploring which plants co-occur naturally falls under the scope of basic science. Image by Brisbane City Council (CC-BY).

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.

A layperson (nonscientist) may perceive applied science as “useful” and basic science as “useless”, posing the question, "What for?" to a scientist advocating knowledge acquisition. 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 $2.4.b$) 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 $2.4.b$: 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)

The discovery of penicillin, the first antibiotic, also originated in basic science. The mold *Penicillium* (figure $2.4.c$) contaminated petri dishes of bacteria and unexpectedly inhibited their growth. Read more about The Real Story behind Penicillin.

Figure $2.4.c$: The mold *Penicillium* growing on a petri dish. Image by Crulina 98 (CC-BY-SA).

Ecological modeling, which is closely intertwined with the field of environmental science, is another example in which applied science closely relies on basic science. **Ecological models** are complex equations through which computers can predict the outcome of different decisions or scenarios based on existing data. For example, a forest manager might use a model to determine which pattern of tree removal will promote forest health and produce a steady, sustainable supply of timber. The data used to create the ecological model are collected through a combination of basic and applied studies.

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2.5: Data Dive- Tonsillectomy Trends

Overview:

Tonsils (specifically the palatine tonsils) are a pair of soft tissue masses that vary in size from person to person, located adjacent to the throat (pharynx). Tonsils are part of the lymphatic organ system, which aids in fighting infections alongside the immune system. Like lymph nodes, tonsils can swell in response to infection. In the height of its popularity in the 1930's, tonsillectomies were viewed essential by the medical community because swelling was viewed as a result of disease rather than a physiological response to infection. Between the 1940's and 1970's evidence began accumulating that there was a correlation between tonsillectomies and contracting bulbar poliomyelitis (aka polio). In the 1970's, evidence then started accumulating that tonsillectomies didn't significantly decrease contracting sore throats and other throat infections as originally thought. As such, tonsillectomy rates have declined as scientific method based research guided the medical community to enforce stricter policies on when the procedure is appropriate. Figure 1.2.5.a below is indicates tonsillectomy rates in Scotland for 20+ years:

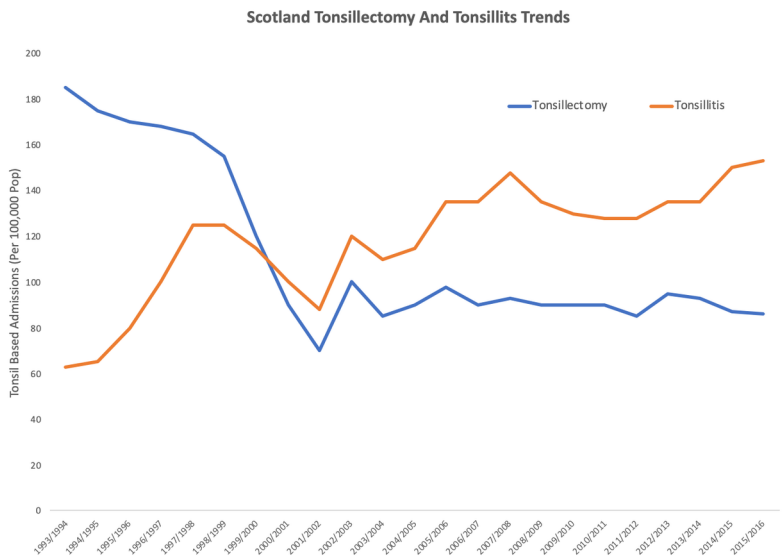

Figure $2.5.a$ Scotland tonsillectomy and tonsillitis trends from 1993 to 2016. Graph created by Rachel Schleiger (CC-BY-NC) modified from data in Douglas CM, Altmyer U, Cottom L, Young D, Redding P, and Clark LJ. 2019.

Questions:

1. What kind of graph is this?
2. What is the independent (explanatory) variable and the dependent (response) variable?
3. What question(s) are the authors trying to answer with this graph?
4. Describe the trend you see for tonsillectomies and tonsillitis from 1993 to 2016.
5. In 1998 new policies were put in place restricting when a tonsillectomy could take place. How did this affect the trends after 1998?
6. What does the results of this graph make you curious about?

Raw Data For Above Graph(s)

Table $2.5.a$ Raw data for Scotland tonsillectomy and tonsillitis trends from 1993 to 2016. Graph created by Rachel Schleiger (CC-BY-NC) modified from data in Douglas CM, Altmyer U, Cottom L, Young D, Redding P, and Clark LJ. 2019.

Years	Tonsillectomy Count	Tonsillitis Count
1993/1994	185	63
1994/1995	175	65
1995/1996	170	80
1996/1997	168	100
1997/1998	165	125
1998/1999	155	125
1999/2000	120	115
2000/2001	90	100
2001/2002	70	88
2002/2003	100	120
2003/2004	85	110
2004/2005	90	115
2005/2006	98	135
2006/2007	90	135
2007/2008	93	148
2008/2009	90	135
2009/2010	90	130
2010/2011	90	128
2011/2012	85	128
2012/2013	95	135
2013/2014	93	135
2014/2015	87	150
2015/2016	86	153

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2.6: Review

Summary

After completing this chapter you should be able to...

- Describe the purpose of science.
- Distinguish between objective and subjective observations.
- Distinguish between quantitative measurements and qualitative observations.
- Distinguish between inductive and deductive reasoning and relate them to descriptive and hypothesis-based science.
- Outline the steps of the scientific method and explain its cyclical nature.
- Distinguish between manipulative experiments and observational studies.
- Identify the types of variables, control group, and replicates in a scientific study.
- Discuss the importance of peer review.
- Distinguish between basic and applied science and provide examples of the value of basic science.

Science is a means of systematically gathering information about the natural world. Science is based on **objective** observations, and following the scientific method helps scientists limit **bias**. Both **induction** and **deduction** are important to the scientific method. Observations lead to a question and hypothesis, an example of inductive reasoning. Making **falsifiable predictions** based on the hypothesis and testing them through **manipulative experiments** or **observational studies** requires deductive reasoning. Finally the results are collected and scientists conclude whether the data support the hypothesis. The scientific method is a cyclical process, in which the latter steps of the process can lead back to earlier steps.

Scientists publish their findings in **scientific journals**, which require **peer review**.

Applied science focuses on solving modern problems, but **basic science** simply focuses on expanding knowledge. However, the findings of basic science can later have useful applications.

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3: MATH BLAST- AN OVERVIEW OF ESSENTIAL MATHEMATICS USED IN SCIENCE

Chapter Hook

Are wildfires getting more destructive and deadly than ever? It is difficult to know for sure without diving into recent and historical fire data. Currently, available data supports that wildfires are worse on both counts. As such, policy makers can utilize this knowledge to create measures to better protect lives and property. Mathematics, especially statistics, is the keystone to successful application and inquiry of the scientific method. In some cases, it also provides a high level of confidence that actions taken will not likely be a waste of time or money.

Figure $3.a$ A wildfire in a California forest. Image by Noah Berger (Public domain)

What is mathematics and statistics?

Mathematics is the abstract science of numbers, quantity and space. Mathematics may be studied in its own right (pure mathematics), or as it is applied to scientific disciplines such as (applied mathematics).

Statistics is a mathematical body of science that pertains to the collection, analysis, interpretation or explanation, and presentation of data, or as a branch of mathematics.

How does mathematics and statistics integrate into the scientific method?

Mathematics and statistics are vital for scientific inquiry. It is an especially imperative tool for disciplines that are inherently variable and require extensive collection of data. Ideally scientists would like to collect data from every individual in the population of interest, but this is rarely possible. As a result, scientists often must use data collected from a representative sample of individuals to draw inferences about basic biological phenomena for a population. This is where mathematics and statistics steps into the party.

What are the most important functions of statistics?

Some of the most important functions of statistics include:

- Description and summary of basic findings (Descriptive statistics).
- Testing hypotheses regarding relationships between variables so the cause and effect can begin to be understood (Inferential statistics).
- Presenting findings in an easily understood manner – misunderstandings keep science from moving forward!

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- Math Blast

3.1: Getting down the basics- What are the essential mathematical and statistical terms and concepts?

3.2: Summarizing the data- Descriptive statistics

3.3: Putting it all together- Inferential statistics and hypothesis testing

3.4: Data Dive- California Wildfires

3.5: Review

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3.1: Getting down the basics- What are the essential mathematical and statistical terms and concepts?

General terms:

- Data – Systematically recorded information.
- Value – Each measurement or observation
- Variable – The object being controlled, manipulated, measured or observed. There are two main types:
  - Independent (explanatory) – The variable that you think will affect what is being measured/observed.
  - Dependent (response) – The variable that is being measured.
- Population – Entire set of objects to be studied.
  - Parameter – Numerical characteristic of population.
- Sample – Sub-collection of objects from population.
  - Statistic – Numerical characteristic of sample from population.

Example

You are a biologist who studies how monarch butterfly (*Danaus plexippus*) populations are affected by habitat destruction. You set up a long-term study to monitor populations in degraded, intact, and restored habitats where monarchs historically have been recorded/observed.

- Population: All monarch butterflies.
- Parameter: Not possible to collect a population worth of data for monarchs. Thus, no parameters can be calculated.
- Sample: Total monarchs observed at each field site during each year of the study.
- Statistic: Any calculations/manipulations from the field site data.

Types of statistics:

- Descriptive statistics – Are calculations to summarize trends in the data. Minimally, measures of center (averages) and spread (standard deviations) from data recorded.
- Inferential statistics – The point of inferential statistics is to take data from the sample to make inferences about the population. Calculations here test hypotheses and try to find/infer cause-and-effect relationships and/or correlations.

It is important to note that statistics can only be helpful if the data from the sample is representative of the population and the interpretation of the data is unbiased!

Types of data:

- Qualitative (categorical) data – Data expressed not in terms of numbers, but rather by means of a natural language description. There are two main types of qualitative data:
  - Ordinal – When categories are in a particular order (ex: large, medium, small)
  - Nominal – When categories have no natural ordering (ex: dog breed, color)

  Graphs types used: Pie, bar

- Quantitative (numerical) data – Data expressed not by means of a natural language description, but rather in terms of numbers. There are two main types of quantitative data:
  - Continuous – Numbers where any integer or fraction can be observed (ex: time, height, or weight)
  - Discrete – A fixed number of outcomes is possible such that there are only whole integers possible (ex: counts)

  Graphs types used: Histograms, line-graphs, scatterplots

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3.2: Summarizing the data- Descriptive statistics

How do you summarize data?

Data is summarized in two main ways: summary calculations and summary visualizations

Calculations: What types of measures are used?

To be able to interpret patterns in the data, raw data must first be manipulated and summarized into two categories of measurements: Measures of central tendency and Measures of variability. These two categories of measurements encapsulate the first step of scientific inquiry, descriptive statistics.

Measures of central tendency (center) – Provides information of how data cluster around some single middle value. There are two measures of center used most often in biological inquiry:

- **Mean** (average) – Sum of all individual values divided by total number of values in sample/population. This is the most commonly used measure of center under symmetrical distribution and is sensitive to outliers.
- **Median** – The middle value when the data set is ordered in sequential rank (highest to lowest). This is commonly used when data is skewed and is resistant to outliers.

Measures of variability (spread) – Describes how spread out or dispersed the data are. There are two main measures of spread used in biological inquiry:

- **Range** – Quantifies the distance between the largest and smallest data values.
- **Standard deviation** – Quantifies the variation or dispersion from the average of a dataset. A low standard deviation indicates that the data tends to be very close to the mean; a high standard deviation indicates that the data points are spread out over a large range of values. This calculation is sensitive to outliers.
- **Standard error** – Quantifies the variation in the means from multiple datasets or a sample distribution of your original dataset.

Visualizing the data: How are tables and graphs used?

After all desired descriptive statistics are calculated, they are typically visually summarized into either a table or graph.

Tables:

A **table** is a set of data values arranged into columns and rows. Typically the columns encompass a broad data category, and the rows encompass another. Within each broad category there are subcategories that determine how many columns and rows the table consists of. Tables are used to both collect and summarize data. However, most of the time when tables are presented, they consist summarized data, not raw data. Although tables allow summarized data to be presented in an orderly manner, most people prefer to translate tables into the more powerful data visualization tool, a graph.

Graphs:

A **graph** is a diagram showing the relation between variable quantities, typically of two variables, each measured along one of a pair of axes at right angles. Graphs can look like a chart or drawing. Most graphs use bars, lines, or parts of a circle to display data. However, there are sometimes when graphs are overlaid on top of maps to also display geographical location, or are even animated to be interactive.

Major graph type categories:

- **Circle/Pie** – A circular chart divided into slices to illustrate numerical proportion. In a pie chart, the arc length of each slice (and consequently its central angle and area), is proportional to the quantity it represents. While it is named for its

resemblance to a pie which has been sliced, there are variations on the way it can be presented.

- **Line** – A type of chart which displays information as a series of data points called 'markers' connected by straight line segments. It is a basic type of chart common in many fields. It is similar to a scatter plot except that the measurement points are ordered (typically by their x-axis value) and joined with straight line segments. A line chart is often used to visualize a trend in data over intervals of time – a time series – thus the line is often drawn chronologically.

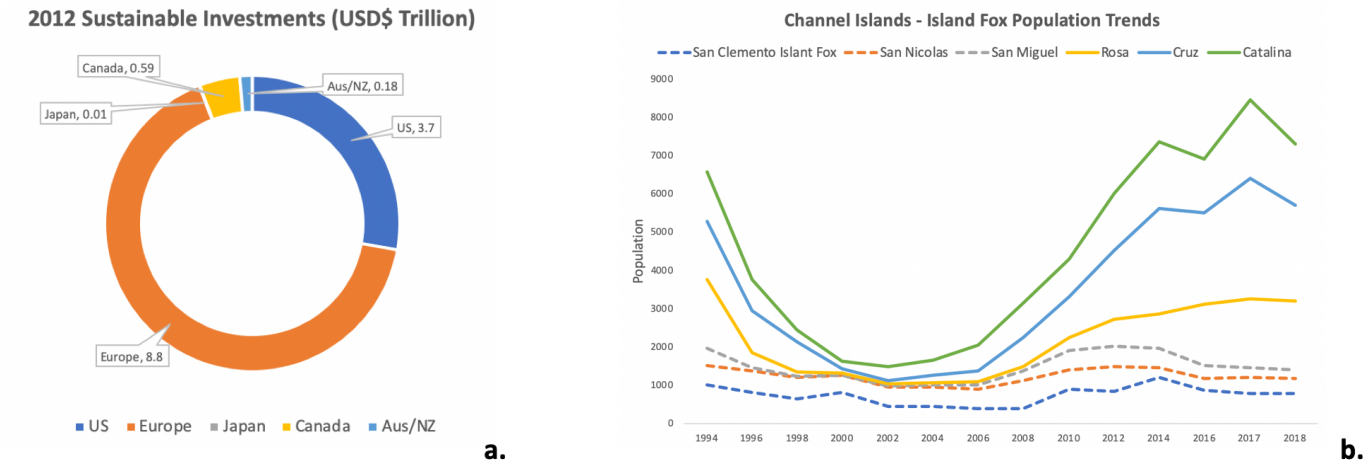

Figure $3.2.a$: Examples of a circle/pie graph (a.) and a line graph (b.). Image created by Rachel Schleiger (CC-BY-NC).

- **Scatter plot** – Is a graph in which the values of two variables are plotted along the horizontal and vertical axes, the pattern of the resulting points revealing any correlation preset. The data are displayed as a collection of points, each having the value of one variable determining the position on the horizontal axis and the value of the other variable determining the position on the vertical axis.

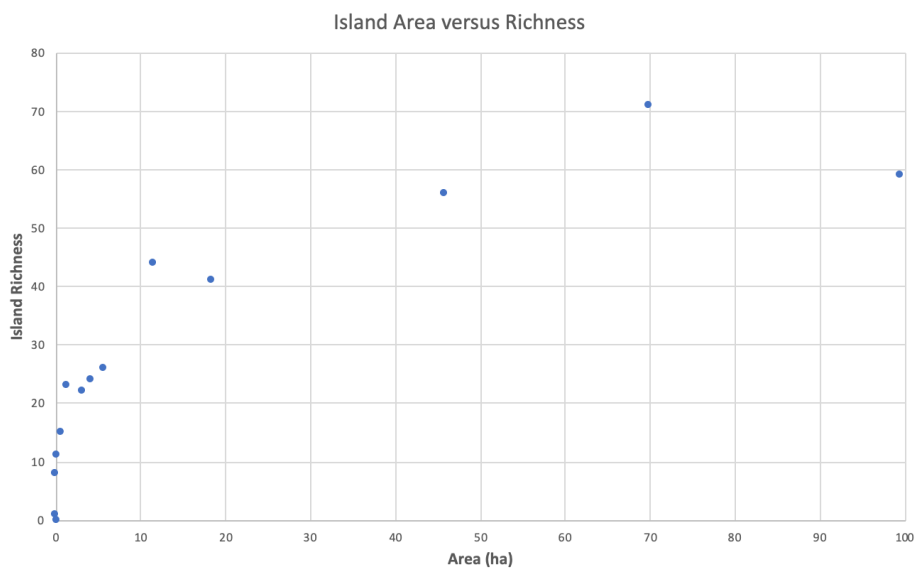

Figure $3.2.b$: Example of a scatter plot. Image created by Rachel Schleiger (CC-BY-NC).

- **Bar** – A chart or graph that presents categorical data with rectangular bars with heights or lengths proportional to the values that they represent. The bars can be plotted vertically or horizontally.
- **Histogram** – Is an approximate representation of the distribution of numerical data. To construct a histogram, the first step is to "bin" (or "bucket") the range of values—that is, divide the entire range of values into a series of intervals—and then count how many values fall into each interval. The bins are usually specified as consecutive, non-overlapping intervals of a variable. The bins (intervals) must be adjacent (meaning there are not spaces between them like there are in bar graphs), and are often

(but not required to be) of equal size. If the bins are of equal size, a rectangle is erected over the bin with height proportional to the frequency—the number of cases in each bin.

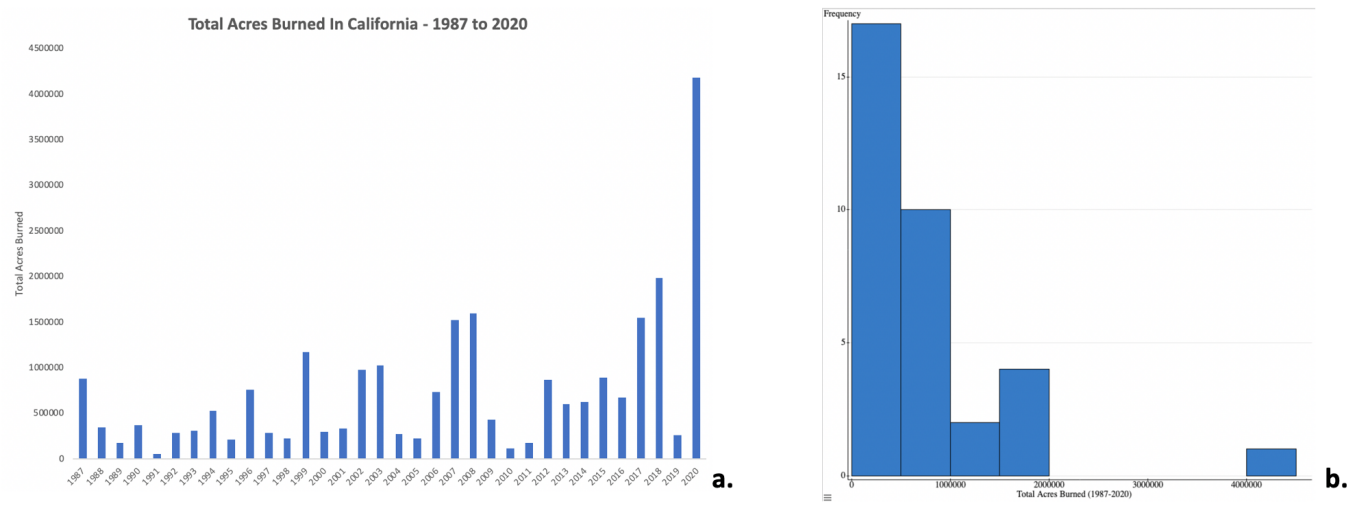

Figure 3.2.c: Examples of a bar graph (a.) and a histogram (b.) using the same dataset. Image created by Rachel Schleiger (CC-BY-NC).

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3.3: Putting it all together- Inferential statistics and hypothesis testing

What is a hypothesis and are there different kinds?

Biological (Scientific) hypothesis: An idea that proposes a tentative explanation about a phenomenon or a narrow set of phenomena observed in the natural world. This is the backbone of all scientific inquiry! As such it is important to have a solid biological hypothesis before moving forward in the scientific method (i.e. procedures, results, discussion). After the creation of a solid biological hypothesis, it can then be simplified into a statistical hypothesis (as defined below) that will become the basis for how the data will be analyzed and interpreted.

Statistical hypotheses: After defining a strong biological hypothesis, a statistical hypothesis can be created based on what you will predict will be the measured outcome(s) (dependent variable(s)). If a study has multiple measured outcomes there can be multiple statistical hypotheses. Each statistical hypothesis will have two components (Null and Alternative).

- **Null hypothesis** (Ho) –This hypothesis states that there is no relationship (or no pattern) between the independent and dependent variables.
- **Alternative hypothesis** (H1) – This hypothesis states that there is a relationship (or is a pattern) between the independent and dependent variables.

Independent versus dependent variables: For both biological and statistical hypotheses there should be two basic variables defined:

- **Independent (explanatory) variable** – It is usually what phenomena you think will affect the measure you are interested in (dependent variable).
- **Dependent (response) variable** – A dependent variable is what you measure in the experiment and what is affected during the experiment. The dependent variable responds to (depends on) the independent variable. In a scientific experiment, you cannot have a dependent variable without an independent variable.

Example

Yellow-billed Cuckoo nests were counted during breeding season in degraded, restored, and intact riparian habitats to see overall habitat preference for nesting sites increased with habitat health.

- Scientific hypothesis: Yellow-billed Cuckoo will have habitat preferences because of habitat health/status.
- Statistical hypotheses: (Ho) There will be no differences in number of nests between habitats with different health/status. (H1) There will be more nests in restored and intact habitats compared to degraded.
- Independent variable = Habitat health/status
- Dependent variable = Number of nests counted

How do you make conclusions?

Finally, after defining the biological hypothesis, statistical hypothesis, and collecting all your data, a researcher can begin statistical analysis. A statistical test will mathematically “test” your data against the statistical hypothesis. The type of statistical test that is used depends on the type and quantity of variables in the study, as well as the question the researcher wants to ask. After computing the statistical test, the outcome will indicate which statistical hypothesis is more likely. This, in turn indicates to scientists what level of inference can be gained from the data compared to the biological hypothesis (the focus point of the study). Then a conclusion can be made based on the sample about the entire population. It is important to note that the process does not stop here. Scientists will want to continue to test this conclusion until a clear pattern emerges (or not) or to investigate similar but different questions.

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3.4: Data Dive- California Wildfires

Overview

When the United States Forest Service was established in 1905 it was declared that, “Today we understand that forest fires are wholly within the control of men.” Humanity assumes time and time again that nature can be controlled, and the National Forest Service were shown how wrong their assumption was 5 years later... The Great Fire of 1910 burned about 3 million acres and killed 86 people. As a consequence of this fire, serious fire suppression policies were put in place and Smokey The Bear was slapped onto posters to represent the cause. At that point, Smokey the Bear told us, "only you can prevent forest fire," indicating that all fire is bad. It has only been in the last couple decades have these policies been questioned and the repercussions of fire suppression of them realized. Now Smokey has updated the saying to, "only you can prevent wildfire," indicating that only some types of fire are bad. The figure below illustrates the number of acres burned in California between 1987 and 2020:

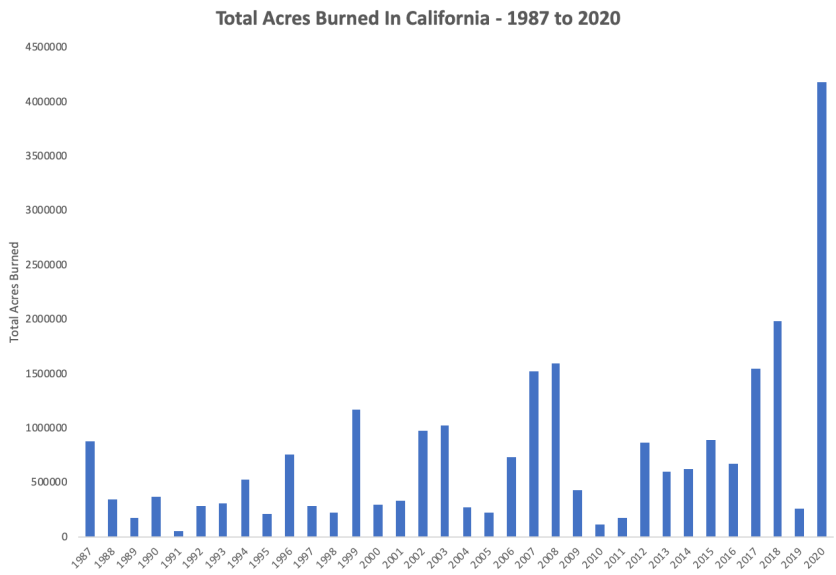

Figure $3.4.a$**:** Total acres burned through the years in California. Graph created by Rachel Schleiger (CC-BY-NC) modified from data collected by CalFire

Questions

1. What kind of graph is this?
2. What is the independent (explanatory) variable and the dependent (response) variable?
3. What question(s) are the authors trying to answer with this graph?
4. What trend(s) can be observed in this graph? Support your answer by referring to appropriate patterns in the graph.
5. How can we use the results of this graph to inform future fire policies/projects/etc?
6. What does the results of this graph make you curious about?

Raw Data For Above Graph(s)

Table $3.4.a$**:** Raw data table of total acres burned through the years in California. Table by Rachel Schleiger (CC-BY-NC) modified from data collected by CalFire

Year	Total Acres Burned
1987	873000

Year	Total Acres Burned
1988	345000
1989	173400
1990	365200
1991	44200
1992	282745
1993	309779
1994	526219
1995	209815
1996	752372
1997	283885
1998	215412
1999	1172850
2000	295026
2001	329126
2002	969890
2003	1020460
2004	264988
2005	222538
2006	736022
2007	1520362
2008	1593690
2009	422147
2010	109529
2011	168545
2012	869599
2013	601635
2014	625540
2015	893362
2016	669534
2017	1548429
2018	1975086
2019	259823
2020	4177856

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3.5: Review

Summary

After completing this chapter you should be able to...

- Know how mathematics and statistics fits into the scientific method
- Define the basic mathematical terms
- Know what data is what what types of data there are
- Understand the difference between descriptive and inferential statistics
- Have a general idea of what types of graphs there are to help visualize data
- Understand the difference between scientific and statistical hypotheses
- Know the process for how conclusions are made

Statistics are based on samples of data collected to be representative of a population of interest due to the impossibility of collecting a complete dataset. There are two types of statistics, **descriptive** (summary calculations) and **inferential** (hypothesis testing). **Data** can come from anywhere! There are two main types of data, **qualitative** (categorical) and **quantitative** (numerical).

For descriptive statistics, measures of **center** and **spread** are commonly calculated in addition to some sort of visualization of the data. The type of calculations and visualizations used depend on the study parameters and objectives.

For inferential statistics, **hypotheses** are clearly defined and analyses are run. There are two main types of hypotheses, **scientific** and **statistical**. The scientific proposes a potential explanation about a phenomenon while a statistical is used to predictions about measured outcomes and has two forms, **null** and **alternative**. **Independent** and **dependent** variables are used to structure the ideas outlined in the hypotheses. Once a study is performed to test the hypotheses then conclusions can be drawn based on evidence identified for each hypothesis.

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UNIT 2: ECOLOGY

Ecology is the study of the interactions of living organisms with their environment. One core goal of ecology is to understand the distribution and abundance of living things in the physical environment. Attainment of this goal requires the integration of scientific disciplines inside and outside of biology, such as biochemistry, physiology, evolution, biodiversity, molecular biology, geology, and climatology. Some ecological research also applies aspects of chemistry and physics, and it frequently uses mathematical models.

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

Humans are a part of the ecological landscape, and human health is one important part of human interaction with our physical and living environment. Lyme disease, for instance, serves as one modern-day example of the connection between our health and the natural world. More formally known as Lyme borreliosis, Lyme disease is a bacterial infection that can be transmitted to humans when they are bitten by the deer tick (*Ixodes scapularis*), which is the primary vector for this disease (figure $2.a$). However, not all deer ticks carry the bacteria that will cause Lyme disease in humans, and *I. scapularis* can have other hosts besides deer. In fact, it turns out that the probability of infection depends on the type of host upon which the tick develops: a higher proportion of ticks that live on white-footed mice carry the bacterium than do ticks that live on deer. Knowledge about the environments and population densities in which the host species is abundant would help a physician or an epidemiologist better understand how Lyme disease is transmitted and how its incidence could be reduced.

(a) (b) (c)

Figure $2.a$: The (a) deer tick carries the bacterium that produces Lyme disease in humans, often evident in (b) a symptomatic bull's eye rash. The (c) white-footed mouse is one well-known host to deer ticks carrying the Lyme disease bacterium. (credit a: modification of work by Scott Bauer, USDA ARS; credit b: modification of work by James Gathany, CDC; credit c: modification of work by Rob Ireton)

Ecologists ask questions across four levels of biological organization—organismal, population, community, and ecosystem. At the organismal level, ecologists study individual organisms and how they interact with their environments. At the population and community levels, ecologists explore, respectively, how a population of organisms changes over time and the ways in which that population interacts with other species in the community. Ecologists studying an ecosystem examine the living species (the biotic components) of the ecosystem as well as the nonliving portions (the abiotic components), such as air, water, and soil, of the environment. The objective of this unit will be to further explore these topics and how they connect to and overlap with environmental science.

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Thumbnail image - "Orchid mantis" is in the Public Domain

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4: Ecology Overview

Levels of Ecological Study

When a discipline such as biology is studied, it is often helpful to subdivide it into smaller, related areas. For instance, cell biologists interested in cell signaling need to understand the chemistry of the signal molecules (which are usually proteins) as well as the result of cell signaling. Ecologists interested in the factors that influence the survival of an endangered species might use mathematical models to predict how current conservation efforts affect endangered organisms. To produce a sound set of management options, a conservation biologist needs to collect accurate data, including current population size, factors affecting reproduction (like physiology and behavior), habitat requirements (such as plants and soils), and potential human influences on the endangered population and its habitat (which might be derived through studies in sociology and urban ecology). Within the discipline of ecology, researchers work at four specific levels, sometimes discretely and sometimes with overlap: organism, population, community, and ecosystem (figure $4.a$).

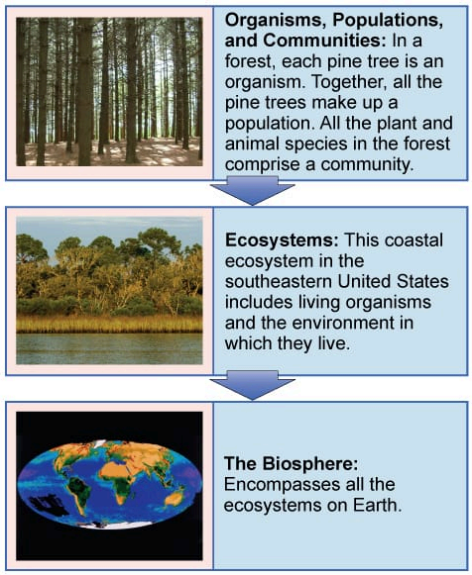

Figure $4.a$: Ecologists study within several biological levels of organization. (credit “organisms”: modification of work by "Crystl"/Flickr; credit “ecosystems”: modification of work by Tom Carlisle, US Fish and Wildlife Service Headquarters; credit “biosphere”: NASA)

Organismal Ecology

Researchers studying ecology at the organismal level are interested in the adaptations that enable individuals to live in specific habitats. These adaptations can be morphological, physiological, and behavioral. For instance, the Karner blue butterfly (*Lycaeides melissa samuelis;* figure $4.b$) 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 $4.b$**:** The Karner blue butterfly (*Lycaeides melissa samuelis*) is a rare butterfly that lives only in open areas with few trees or shrubs, such as pine barrens and oak savannas. It can only lay its eggs on lupine plants. (credit: modification of work by J & K Hollingsworth, USFWS)

After hatching, the larval caterpillars emerge and spend four to six weeks feeding solely on wild lupine (figure $4.c$). The caterpillars pupate (undergo metamorphosis) and emerge as butterflies after about four weeks. The adult butterflies feed on the nectar of flowers of wild lupine and other plant species. 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).

Figure $4.c$**:** The wild lupine (*Lupinus perennis*) is the host plant for the Karner blue butterfly

Population Ecology

A population is a group of interbreeding organisms that are members of the same species living in the same area at the same

time. (Organisms that are all members of the same species are called conspecifics.) A population is identified, in part, by where it lives, and its area of population may have natural or artificial boundaries: natural boundaries might be rivers, mountains, or deserts, while examples of artificial boundaries include mowed grass, manmade structures, or roads. The study of population ecology focuses on the number of individuals in an area and how and why population size changes over time. 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 is 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, Karner blue butterfly larvae form mutualistic relationships with ants. Mutualism is a form of a 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.

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 the abiotic components (non-living things) of that area. Some of the abiotic components include air, water, and soil. Ecosystem biologists ask questions about how nutrients and energy are stored and 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, though the biotic and abiotic portions of the ecosystem.

Career Connection: Ecologist

A career in ecology contributes to many facets of human society. Understanding ecological issues can help society meet the basic human needs of food, shelter, and health care. Ecologists can conduct their research in the laboratory and outside in natural environments (Figure $4.d$). These natural environments can be as close to home as the stream running through your campus or as far away as the hydrothermal vents at the bottom of the Pacific Ocean. Ecologists manage natural resources such as white-tailed deer populations (*Odocoileus virginianus*) for hunting or aspen (*Populus* spp.) timber stands for paper production. Ecologists also work as educators who teach children and adults at various institutions including universities, high schools, museums, and nature centers. Ecologists may also work in advisory positions assisting local, state, and federal policymakers to develop laws that are ecologically sound, or they may develop those policies and legislation themselves. To become an ecologist requires an undergraduate degree, usually in a natural science. The undergraduate degree is often followed by specialized training or an advanced degree, depending on the area of ecology selected. Ecologists should also have a broad background in the physical sciences, as well as a sound foundation in mathematics and statistics.

Figure $4.d$**:** This landscape ecologist is releasing a black-footed ferret into its native habitat as part of a study. (credit: USFWS Mountain Prairie Region, NPS)

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5: POPULATIONS

Chapter Hook

Roadkill, we've all seen it on the roadside. It is just one very unfortunate outcomes of our extensive road networks. Roads, especially freeways and busy highways, also break apart habitats. When habitats are broken up into smaller pieces it weakens wildlife populations which need to move freely across landscapes for resources, refuge, and mates. Over long time scales, these fragmented habitats decrease species diversity, weaken species population gene pools, and can lead to extirpation (elimination of local population(s)) and extinction. As a result of numerous studies, ecologists have found one solution, wildlife crossings (aka green corridors or wildlife corridors). Wildlife crossings look like an underpass or overpass. However, they are filled with dirt and plants to look more natural. These crossings enable wildlife populations to move more freely, and safely, across landscapes all over the globe.

Figure $5.a$: A newly constructed wildlife overpass over a Singapore highway. Image by Benjamin P. Y-H. Lee (licensed under CC-BY-4.0)

Populations are interacting and interbreeding groups of individuals from the same species in a common area. The study of **population ecology** focuses on population size and the factors that regulate population growth.

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5.1: Population Dispersion

5.2: Population Size

5.3: Population Growth and Regulation

5.4: Life History

5.5: Data Dive- Wildlife Corridors

5.6: Review

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5.1: Population Dispersion

The **dispersion pattern** (distribution pattern) of a population describes the arrangement of individuals within a habitat at a particular point in time, and broad categories of patterns are used to describe them. The three dispersion patterns are clumped, random, and uniform (figure $5.1.a$).

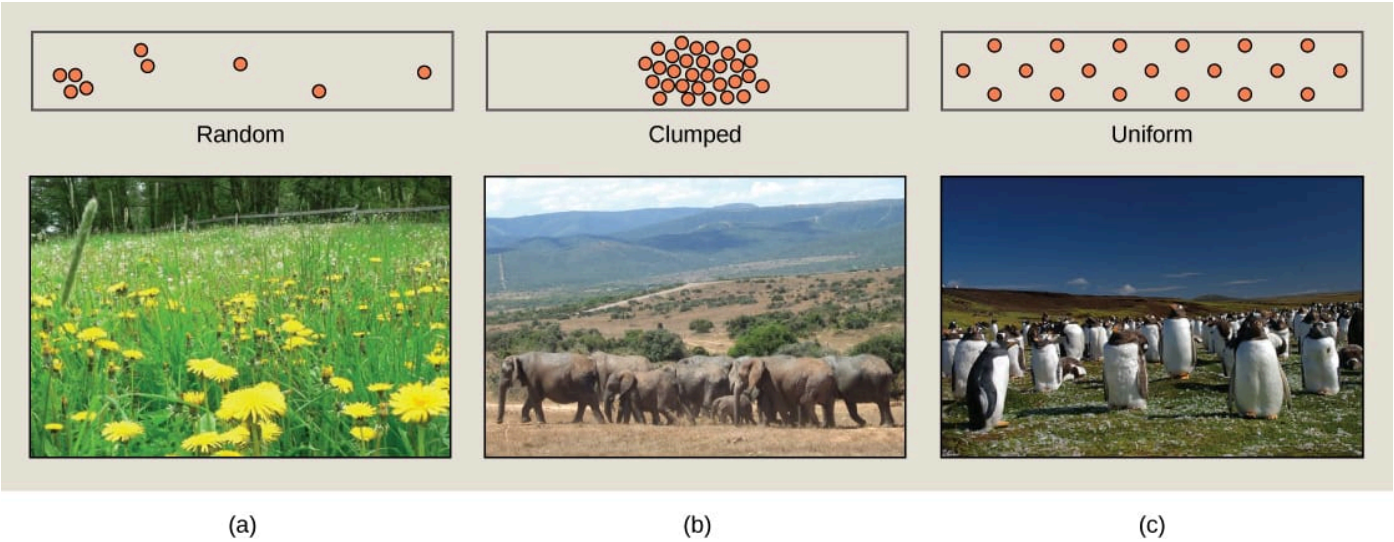

Figure $5.1.a$: Species may have a random, clumped, or uniform distribution. Plants such as (a) dandelions with wind-dispersed seeds tend to be randomly distributed (represented by dots in no particular pattern). Animals such as (b) elephants that travel in groups exhibit a clumped distribution (represented by dots clustered together). Territorial birds such as (c) penguins tend to have a uniform distribution (represented by dots evenly spaced from each other). (credit a: modification of work by Rosendahl; credit b: modification of work by Rebecca Wood; credit c: modification of work by Ben Tubby)

Individuals that are grouped into patches have a **clumped distribution**, or aggregated distribution. This can occur if resources are distributed unequally; for example, pipevine swallowtail caterpillars would be clumped in areas with their host plant, California pipevine. Clumped distribution may also reflect the locations of suitable microhabitats, such as an herbaceous (non-woody) plant species that only grows in the shade clustering under trees. Plants that drop their seeds straight to the ground, such as oak trees, may also have this distribution. Finally, social behavior in animals results in a clumped distribution, such as wolves hunting in a pack, a herd of elephants, or a school of fish traveling together for safety.

Populations that have a **random distribution** are not arranged in any particular pattern. Some individuals may be close together while others may be far apart. 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.

Individuals that are equally spaced in the environment have a **uniform distribution**. Saguaro cacti are evenly spaced due to limited resources in the desert. (There is not sufficient water to support two large cacti side-by-side.) Uniform distributions can result from **interference competition**, when individuals take pre-emptive measures to avoid competition for resources. For example, some plants that secrete substances inhibiting the growth of nearby individuals (such as the release of toxic chemicals by sage plants), a phenomenon called **allelopathy**. Another example of interference competition occurs 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 (see Population Size and Density).

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5.2: Population Size

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; figure $5.2.a$). 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, the ability of individuals to find a mate, and diseases spread. (Dispersion patterns can also affect these factors; for example, a solitary species with a random distribution might have difficulty finding a mate when compared to social species clumped together in groups.) Smaller organisms tend to be more densely distributed than larger organisms (figure $5.2.b$).

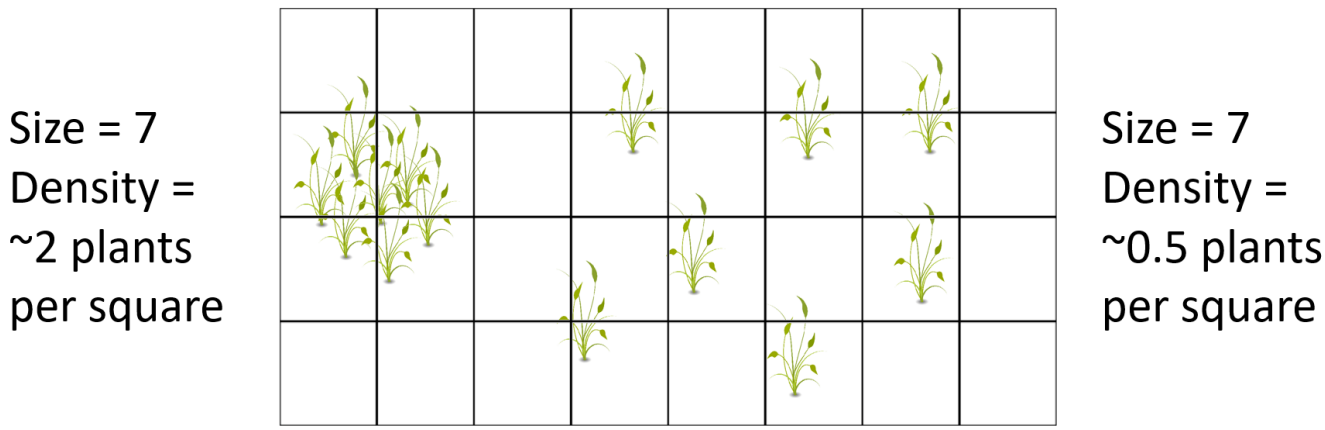

Figure $5.2.a$: Both populations shown contain seven plants, so their populations size is the same. However, the population on the left has a higher population density (2 plants per square) than the population on the right (density = 0.5 plants per square). Image by Melissa Ha using Green Plant (public domain).

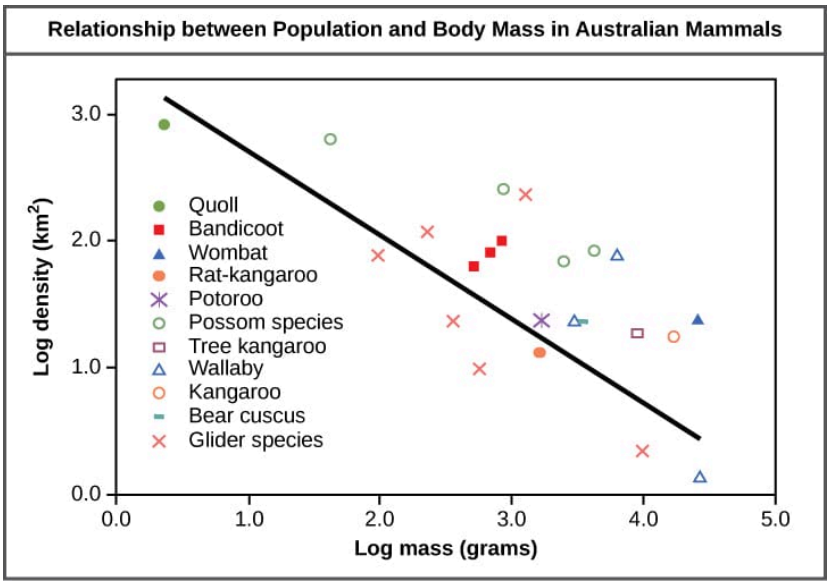

Figure $5.2.b$: Australian mammals show a typical inverse relationship between population density and body size. Log mass in grams is on the x-axis, and log density in square kilometers (km^2) is on the y-axis. Each data point represents a different species, including the quoll, four bandicoot species, wombat, rat-kangaroo, potoroo, four possom species, tree kangaroo, three wallaby species, kangaroo, bear cuscus, and six glider species. As this graph shows, population density typically decreases with increasing body size. For example, quolls have the lowest body mass and the highest density. The heaviest wallaby species has the lowest population density.

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 using 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 (Figure $5.2.c$). 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.

Figure $5.2.c$: High schoolers using a quadrat in an intertidal zone. Image by kqedquest (CC-BY-NC)

For smaller mobile organisms, such as mammals, a technique called **mark and recapture** is often used. This method involves

marking captured animals and releasing them back into the environment to mix with the rest of the population. Later, a new sample is captured and scientists determine how many 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:

$$N = \frac{(\text{number marked first catch} \times \text{total number of second catch})}{\text{number marked second catch}} \tag{5.2.1}$$

Using our example, the equation would be:

$$\frac{(80 \times 100)}{20} = 400 \tag{5.2.2}$$

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.

The mathematical methods required to estimate population sizes can be influenced by dispersion pattern.

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5.3: 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.

The Population Growth Rate (*r*)

The **population growth rate** (sometimes called the rate of increase or per capita growth rate, *r*) equals the **birth rate** (*b*) minus the **death rate** (*d*) divided by the **initial population size** (N_0).

$$r = (b - d) \div N_0$$

Another method of calculating the population growth rate involves final and initial population size (figure $5.3.a$). In this case, **population growth rate** (*r*) equals the **final population size** (N) minus the **initial population size** (N_0) and divided by the **initial population size** (N_0).

$$r = (N - N_0) \div N_0$$

Figure $5.3.a$: How could we calculate the growth rate of this caribou population per year if there were 200 individuals in 2016 and 300 individuals in 2018? Image by K. Joly/NPS (public domain).

Doubling Time

The **doubling time** is how long it will take for a population to become twice its initial size. The **doubling time** (*t*) is equal to 0.69 divided by the **population growth rate** (*r*), written as a proportion.

$$t = 0.69 \div r$$

Population ecologists sometimes round this equation and calculate doubling time using the **"Rule of 70"** (dividing 70 by the population growth rate, written as a percentage). To express population growth rate as a percentage, it is multiplied by 100%.

Thus, the 0.69 in the original doubling time equation is also multiplied by 100. This value (69) is rounded to 70 for simplicity.

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 $5.3.b$).

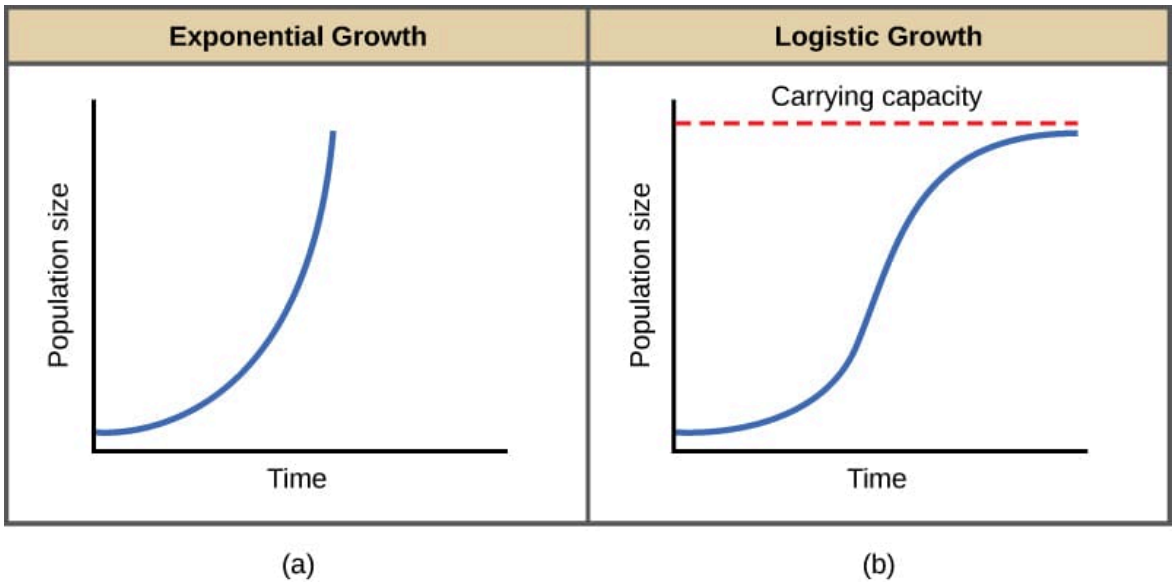

Figure $5.3.b$: These graphs show exponential and logistic growth, with population size on the y-axis and time on the x-axis. When resources are unlimited, populations exhibit (a) exponential growth, shown in a J-shaped curve. When resources are limited, populations exhibit (b) logistic growth. In logistic 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.

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 (figure $5.3.c$). In another hour, each of the 2000 bacteria will divide, producing 4000 bacteria. After the third hour, there should be 8000 bacteria in the flask. The important concept of exponential growth is that the growth rate—the number of organisms added in each reproductive generation—is itself increasing; that is, the population size is increasing at a greater and greater rate. After 24 of these cycles, the population would have increased from 1000 to more than 16 billion bacteria. When the population size, *N*, is plotted over time, a J-shaped growth curve is produced (figure $5.3.b$).

Figure $5.3.c$: Bacteria growing with abundant nutrients in a flask will exhibit exponential growth. Image by Soledad Mirand-Rottman (CC-BY-SA).

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.

In the real world, with its limited resources, exponential growth cannot continue indefinitely. Exponential growth may occur in environments where there are few individuals and plentiful resources, but when the number of individuals gets large enough, resources will be depleted and the growth rate will slow down. Eventually, the growth rate will plateau or level off (figure $5.3.b$). This population size, which is determined by the maximum population size that a particular environment can sustain, is called the **carrying capacity**, symbolized as *K*. In real populations, a growing population often overshoots its carrying capacity and the death rate increases beyond the birth rate causing the population size to decline back to the carrying capacity or below it. Most populations usually fluctuate around the carrying capacity in an undulating fashion rather than existing right at it.

A graph of logistic growth yields the S-shaped curve (figure $5.3.b$). It is a more realistic model of population growth than exponential growth. There are three different sections to an S-shaped curve. Initially, growth is exponential because there are few individuals and ample resources available. Then, as resources begin to become limited, the growth rate decreases. Finally, the growth rate levels off at the carrying capacity of the environment, with little change in population number over time.

While bacteria in a flask with abundant nutrients might initially exhibit exponential growth, bacteria grown with limited nutrients can exhibit logistic growth (figure $5.3.d$).

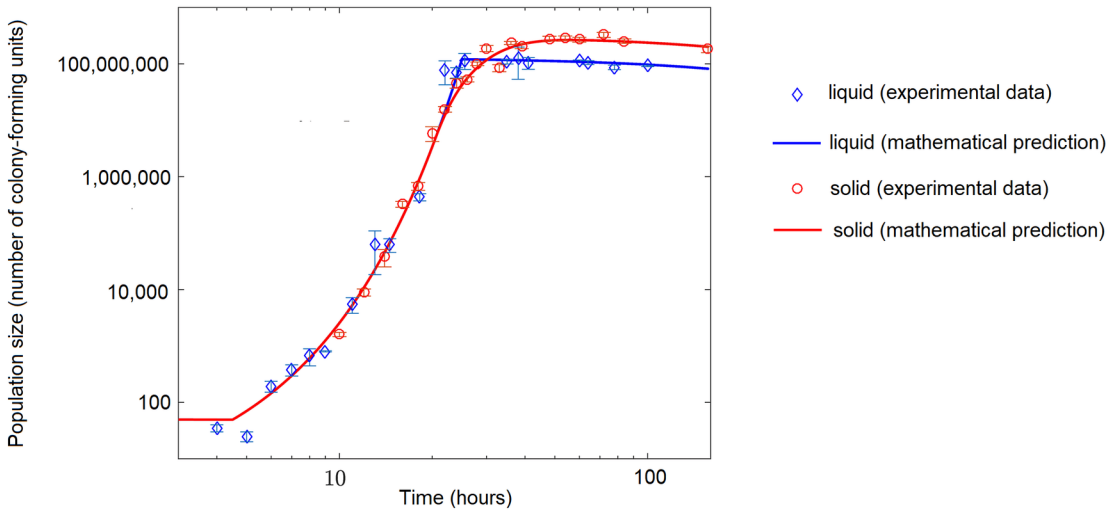

Figure 5.3.d: The growth of the bacterium *Escherichia coli* (*E. coli*) with limited nutrients over time in hours. Population size is in number of colony-forming units, which is a cell capable of dividing to produce a colony of cells. The bacteria were grown in liquid (blue diamonds) or on a semisolid medium (agar, red circles). The points represent actual measurements of populations size, and the lines represent a mathematical model, basically a prediction that is based on the data points. The data show logistic population growth, particularly in solid media. Initially, population size increases rapidly (concave part of curve), but the growth rate then stabilizes (straight line) before decreasing (convex part of curve) and leveling near the carrying capacity. Image modified from Shao X, Mugler A, Kim J, Jeong HJ, Levin BR, Nemenman I (2017) Growth of bacteria in 3-d colonies. PLoS Comput Biol 13(7): e1005679 (CC-BY).

In some populations, there are variations to the S-shaped curve. Examples in wild populations include sheep and harbor seals (figure 5.3.e). 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.

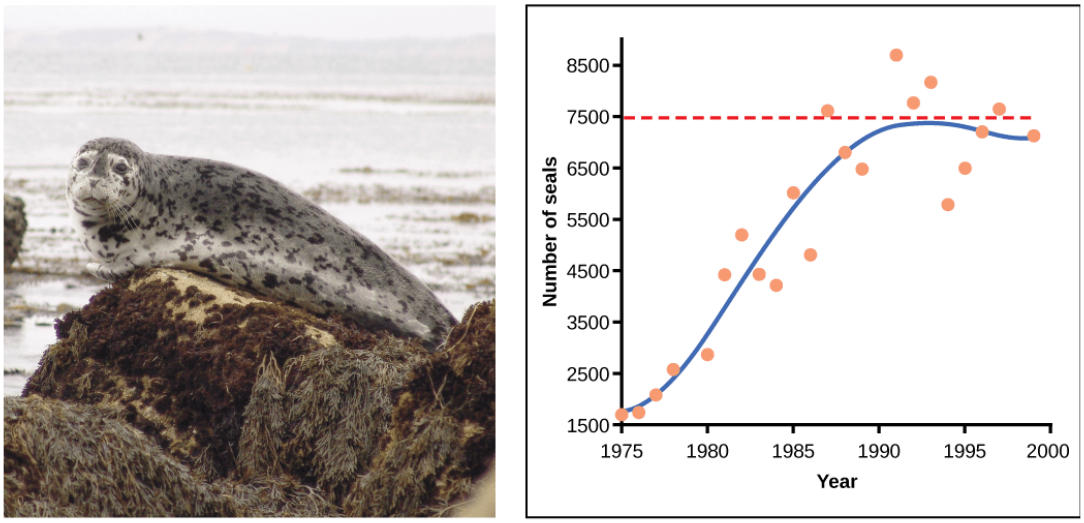

Figure 5.3.e: A natural population of seals shows logistic growth. The number of seals, ranging from 1500 to 8500, is on the y-axis, and the year, ranging from 1975-2000, is on the x-axis. Orange dots represent the observed population size each year, and the blue line represent the trend. From 1975 to 1983, the blue line curves upwards, representing an increase in both population size and population growth rate. From 1983 to 1992, the curve flattens, representing that population size is still increasing, but population growth rate is decreasing. After 1992, population fluctuates near the carrying capacity (dotted, horizontal line).

The logistic population growth model is not the only way that populations respond to limited resources. In some populations, growth is exponential until resources run low, wastes accumulate, or disease spreads (see limiting factors below), and the population then crashes. Thus, population growth rate (and size) may plummet rapidly instead of tapering as it approaches the

carrying capacity.

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. Furthermore, some factors (**growth factors**) increase population growth rate while other factors (**limiting factors**) slow population growth. Examples of growth factors are resources like food, water, and space. Limiting factors can be classified as density-dependent or density-independent.

Density-dependent Regulation

Most **density-dependent factors** are biological in nature (biotic). Usually, the denser a population is, the greater its mortality rate. An example of density-dependent regulation is shown in figure $5.3.f$ with results from a study focusing on the giant intestinal roundworm (*Ascaris lumbricoides*), a parasite of humans and other mammals. Denser populations of the parasite exhibited lower fecundity: they contained fewer eggs. One possible explanation for this is that females would be smaller in more dense populations (due to limited resources) and that smaller females would have fewer eggs. This hypothesis was tested and disproved in a 2009 study which showed that female weight had no influence. The actual cause of the density-dependence of fecundity in this organism is still unclear and awaiting further investigation.

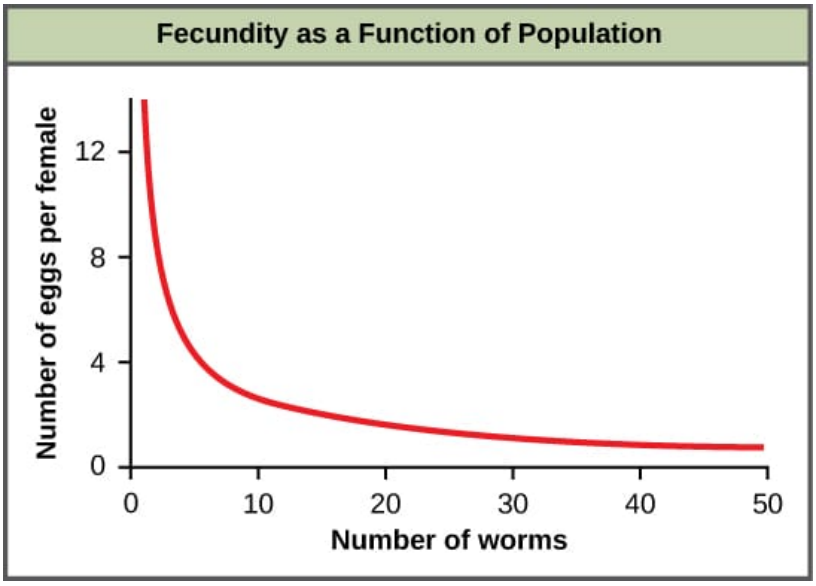

Figure $5.3.f$: In this population of roundworms, fecundity (number of eggs per female) decreases with population size (number of worms). (Note that population size rather than population density is shown here, but population density does correlate with population size.) The number of eggs decreases rapidly at first, then levels off between 30 to 50 worms.

Density-dependent factors include predation, parasitism, herbivory, competition, and accumulation of waste. As a population increases, its predators are able to harvest it more easily. Prey density also affects population growth rate of predators: low prey density increases the mortality of its predator because it has more difficulty locating its food sources.

Parasites are able to pass from host to host more easily as the population density of the host increases. For this reason, epidemics among humans are particularly severe in cities. In fact, for most of the period since humans began living in cities, city populations have been maintained only through continual immigration from the countryside. Not until the development of community sanitation, immunization, and other public health measures did cities avoid periodic sharp drops in population as a result of epidemics. The recurrent epidemics of the "black death" in Europe that began in the fourteenth century caused a sharp decline in population. In just three years (1348–1350), at least one-quarter of the population of Europe died from the disease (probably plague).

Similarly, herbivores can more easily spread between individual plants in a dense population. This is why strip cropping (see

Sustainable Agriculture) helps control pests. An herbivore or plant pathogen may infect one row of plants, but it is less likely to spread to more distant rows of that species.

While **interspecific competition** occurs between different species, **intraspecific competition** occurs when members of the same species harm each other by using the same resources. For example, in the summer of 1980, much of southern New England was struck by an infestation of the gypsy moth (figure $5.3.g$). As the summer wore on, the larvae (caterpillars) pupated, the hatched adults mated, the females laid masses of eggs (each mass containing several hundred eggs) on virtually every tree in the region. In early May of 1981, the young caterpillars that hatched from these eggs began feeding and molting.

Figure $5.3.g$: Gypsy moth caterpillars face intraspecific competition at high densities. Image by Editor at Large (CC-BY-SA).

The results were dramatic: In 72 hours, a 50-ft beech tree or a 25-ft white pine tree would be completely defoliated. Large patches of forest began to take on a winter appearance with their skeletons of bare branches. In fact, the infestation was so heavy that many trees were completely defoliated before the caterpillars could complete their larval development. The result: a massive die-off of the animals; very few succeeded in completing metamorphosis. Here, then, was a dramatic example of how competition among members of one species for a finite resource - in this case, food - caused a sharp drop in population. The effect was clearly density-dependent. The lower population densities of the previous summer had permitted most of the animals to complete their life cycle.

Density-independent Regulation

Density-independent factors, typically physical or chemical in nature (abiotic), influence the mortality of a population regardless of its density, including weather (figure $5.3.h$), natural disasters (earthquakes, volcanoes, fires, etc.), and pollution. An individual deer may be killed in a forest fire regardless of how many deer happen to be in that area. Its chances of survival are the same whether the population density is high or low. The same holds true for cold winter weather.

Figure $5.3.h$: Severe weather, like Hurricane Florence of 2018, can reduce population size regardless of density. Image by NASA Goddard Space Flight Center (CC-BY)

In real-life situations, population regulation is very complicated and density-dependent and independent factors can interact. A dense population that is reduced in a density-independent manner by some environmental factor(s) will be able to recover differently than a sparse population. For example, a population of deer affected by a harsh winter will recover faster if there are more deer remaining to reproduce.

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5.4: Life History

Life history characteristics, are those that relate to the survival, mortality, and reproduction of a species. Examples include birth rates, age at first reproduction, the number of offspring, and death rates. These characteristics evolve just like physical traits or behavior, leading to adaptations that affect population growth.

Reproductive Strategies

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. Population ecologists have described a continuum of life-history "strategies" with *K*-selected species on one end and *r*-selected species on the other (table $5.4.a$). ***K*-selected species** are adapted to stable, predictable environments. Populations of *K*-selected species tend to exist close to their carrying capacity (which is represented by the letter "K" in the equation for logistic population growth). These species tend to have larger, but fewer, offspring, contribute large amounts of resources to each offspring, and have long generation times. Elephants would be an example of a *K*-selected species (figure $5.4.a$). When a habitat becomes filled with a diverse collection of creatures competing with one another for the necessities of life, the advantage shifts to *K*-strategists. *K*-strategists have stable populations that are close to *K*. There is nothing to be gained from a high growth rate (*r*). The species will benefit most by a close adaptation to the conditions of its environment.

Table $5.4.a$***:*** *Comparison of K- and r-selected species*

Characteristics of *K*-selected species	Characteristics of *r*-selected species
Mature late	Mature early
Greater longevity	Lower longevity
Increased parental care	Decreased parental care
Strong competitors	Weak competitors (strong colonizers)
Fewer offspring	More offspring
Larger offspring	Smaller offspring

(a) K-selected species

(b) r-selected species

Figure $5.4.a$: (a) Elephants are considered K-selected species as they live long, mature late, and provide long-term parental care to few offspring. Oak trees produce many offspring that do not receive parental care, but are considered K-selected species based on longevity and late maturation. (b) Dandelions and jellyfish are both considered r-selected species as they mature early, have short lifespans, and produce many offspring that receive no parental care.

***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 (figure $5.4.a$). *r*-strategists have short life spans and reproduce quickly, resulting in short generation times. For example, the housefly can produce 7 generations each year (each of about 120 young). Ragweed is well-adapted to exploiting its environment in a hurry - before competitors can become established. It grows rapidly and produces a huge number of seeds (after releasing its pollen, the bane of many hay fever sufferers). Because ragweed's approach to continued survival is through rapid reproduction (a high value of *r)* it is called an *r*-strategist. Other weeds, many insects, and many rodents are also *r*-strategists. If fact, if we consider an organism a pest, it is probably an *r*-strategist.

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; therefore, each species may have some characteristics that trend toward one extreme or the other. Nevertheless, the *r*- and *K*-selection theory provides a foundation for a more accurate life history framework. New demographic-based models of life history evolution have been developed, which incorporate many ecological concepts included in *r*- and *K*-selection theory as well as population age structure and mortality factors.

Life Tables

Life tables provide important information about the life history of an organism and the life expectancy of individuals at each age. They are modeled after actuarial tables used by the insurance industry for estimating human life expectancy. Life tables may include the probability of each age group dying before their next birthday, the percentage of surviving individuals dying at a particular age interval (their mortality rate, and their life expectancy at each interval). An example of a life table is shown in Table $5.4.b$ 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. Life tables often include more information than shown in Table $5.4.b$, such as fecundity (reproduction) rates for each age group.

Table $5.4.b$***:*** *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

Survivorship Curves

Another tool used by population ecologists is a **survivorship curve**, which is a graph of the number of individuals surviving at each age interval versus time. These curves allow us to compare the life histories of different populations (figure $5.4.c$). There are three types of survivorship curves. In a **type I survivorship 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 survivorship curves**, mortality is relatively constant throughout the entire life span, and mortality is equally likely to occur at any point in the life span. Many bird populations provide examples of an intermediate or type II survivorship curve. In **type III survivorship curves**, early ages experience the highest mortality with much lower mortality rates for organisms that make it to advanced years. Type III organisms typically produce large numbers of offspring, but provide very little or no care for them. Trees and marine invertebrates exhibit a type III survivorship curve because very few of these organisms survive their younger years, but those that do make it to an old age are more likely to survive for a relatively long period of time.

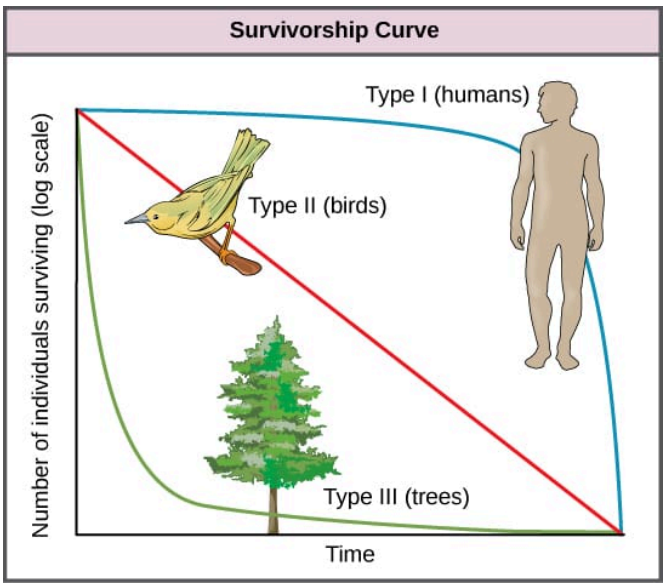

Figure $5.4.c$: Survivorship curves show the chance of survival in a population according to age. The number of individuals surviving (on a log scale) is on the y-axis, and time (representing relative age) is on the x-axis. Humans and most mammals have a Type I survivorship curve, because death primarily occurs in the older years. The Type I survivorship curve is represented by a convex curve, which rapidly declines at the end. Birds have a Type II survivorship curve, as death at any age is equally probable. The Type II survivorship curve is represented by a straight line, going from the upper left to lower right of the graph. 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. The Type III survivorship curve is represented by a concave curve, which initially declines rapidly and then flattens.

While is no exact association between reproductive strategies (*K*- or *r*-selected) and survivorship curves (Type I, II, or III), *K*-selected species are more likely to have a Type III survivorship curve. *r*-selected species tend to have a Type I survivorship curve.

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5.5: Data Dive- Wildlife Corridors

Overview

In 1999 the Sonoran Desert Conservation Plan was created to help wildlife populations and habitats. As a result of this plan, biologists were able to identify landscapes with wildlife barriers and get funding to install wildlife corridors. On State Route (SR) 77 two wildlife corridors were installed, one overpass and one underpass. These corridors were the first of their kind to be built in the Sonoran Desert so it was difficult to estimate what level of success they would have. As such, a monitoring plan was put in place to document which species used the corridors and how often they used it as time passed since their installation. The figure below illustrates the usage of the wildlife corridors 2+ years after their installation:

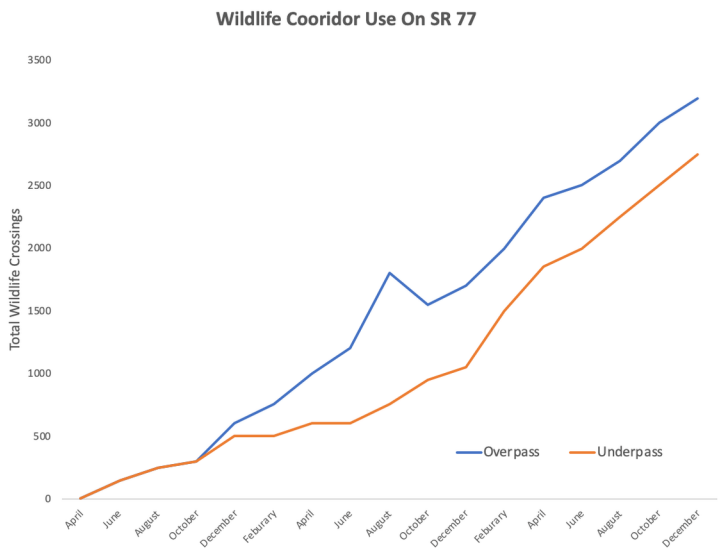

Figure $5.5.a$: Total wildlife crossings after installation for overpass and underpass on SR 77. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Santa Catalina - Tortolita Mountain Corridor Progress Report

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph?
3. Does this graph show a positive or negative relationship between the variables? Support your answer by referring to trends observed in the graph.
4. Do you think like the authors are satisfied with the results in the graph? Why?
5. How can we use the results of this graph to inform future wildlife corridor installations?
6. What information/patterns is not clear from this graph?

Raw Data For Above Graph(s)

Table $5.5.a$**:** Raw data for total wildlife crossings after installation for overpass and underpass on SR 77. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Santa Catalina - Tortolita Mountain Corridor Progress Report

Month	Overpass	Underpass
April	0	0
June	150	150

Month	Overpass	Underpass
August	249	250
October	296	294
December	600	500
February	750	502
April	1000	600
June	1200	605
August	1800	750
October	1550	950
December	1700	1050
February	2000	1500
April	2400	1850
June	2500	2000
August	2700	2250
October	3000	2500
December	3200	2750

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5.6: Review

Summary

After completing this chapter you should be able to...

- Describe three different population dispersion patterns.
- Differentiate between population size and density.
- Explain how ecologists measure population size.
- Calculate population growth rate (r) and doubling time (t).
- Distinguish between exponential and logistic population growth models, explaining the role of the carrying capacity in logistic growth.
- Provide examples of density-dependent and density-independent factors that regulate populations.
- Compare K-selected and r-selected reproductive strategies.
- Interpret life tables.
- Compare type I, type II, and type III survivorship curves.

Populations are interacting, interbreeding groups of individuals from the same species. Ecologists measure characteristics of populations: **dispersion pattern**, **population size**, and **population density**. Populations with unlimited resources grow **exponentially**—with an accelerating growth rate. When resources become limiting, populations follow a **logistic growth curve** in which population size will level off at the **carrying capacity**. **Density-dependent factors** limit population growth as they reach their carrying capacity and include biotic factors such as predation, competition, and disease. Density-independent factors, such as storms and fires, are abiotic and decrease population size regardless of density.

Several frameworks explain how **life history** can influence population dynamics. ***K*-selected species** tend to have long life spans and produce few offspring with much parental care whereas ***r*-selected species** mature and reproduce rapidly, producing many offspring and offering little parental care. **Life tables** are useful to calculate life expectancies of individual population members. **Survivorship curves** show the number of individuals surviving at each age interval plotted versus time.

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6: COMMUNITIES

Chapter Hook

Until the late 1800s, Bison (*Bison bison*) numbered tens of millions in the Great Plains of the United States. By 1890, roughly 1000 Bison were left because the United States government campaign to eradicate the native people, their culture, and habitats they relied on. Slowly, a movement started to try and save Bison from extinction. It took until the early 2000's for Bison numbers to reach a half a million. During this time, scientists were able to observe the Bison reintroduction back into the Great Plains. Bison were found to be the most critical species to restoring and maintaining the function and diversity in the Great Plains community. Both plants and animal populations in the community were strengthened from the return of the Bison. Understanding community dynamics is essential to conserving and restoring these systems and the species that define them. This is particularly critical for communities with one particular species that acts as a keystone to the health of the system.

Figure $6.a$**:** American bison with starlings on its back. Image by NPS photos/Kim Acker (Public Domain)

Populations typically do not live in isolation from other species. Populations that interact within a given area form a **community**. The organisms that form a community are found in **habitats**, physical environments where organisms live; however, **biotic** (living) components are considered part of a community. Scientists study ecology at the community level to understand how species interact with each other and compete for the same resources.

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6.1: BIOTIC INTERACTIONS

Biotic interactions refer to the relationships among organisms. They can be **intraspecific** (between members of the same species) or **interspecific** (between members of different species). When at least one of the interactants is harmed, the relationship is called an **antagonism. Trophic interactions**, in which one species consumes another, are antagonisms. **Competition** is another antagonism in which species at the same trophic level (that eat the same things) interact through using the same resources. Interactions in which at least one species benefits and neither is harmed are called **facilitation**, which can be categorized as **commensalism** or **mutualism.**

Figure $6.1.a$: A variety of biotic interactions occur among the species at The Seal Beach National Wildlife Refuge (top). For example, the Light-Footed Clapper Rail (bottom) benefits from the cordgrass in which it nests. However, predators such as red foxes harm this endangered bird. The refuge manages this harmful interaction by installing fencing to exclude the red fox, which historically did not occur in the area. Top image and bottom image by US Fish & Wildlife Service (public domain).

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6.1.1: TROPHIC INTERACTIONS

Trophic interactions occur when one organism feeds on another. The three main types of trophic interactions are **predation** (figure $6.1.1.a$), **herbivory**, or **parasitism**. During these interactions, one species benefits by gaining food at the expense of the other, which either dies or loses nutrients, tissues, or organs (such as leaves). Trophic interactions involve the flow of energy, and the trophic interactions in a community can be represented by **food chains** and **food webs**.

Figure $6.1.1.a$: A hawk (*Buteo jamaicensis*) eats a vole (*Microtus californicus*), exemplifying predation, a common trophic interaction. Image by Jrockley (public domain).

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6.1.1.1: Predation

Perhaps the classical example of a biotic interaction is the predator-prey relationship. **Predation** occurs when one species (the **predator**) kills and eats multiple **prey** over its lifetime.

Predator-Prey Dynamics

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. For example, 100 years of trapping data from North America shows how population dynamics of the lynx (predator) and the snowshoe hare (prey) cycle (figure $6.1.1.1.a$-b).

Figure $6.1.1.1.a$: The Canada lynx is an example of a predator. Image by Michael Zahra (CC-BY-SA).

Figure $6.1.1.1.b$: The snowshoe hare is the prey of the Canada lynx. Image by the National Park Service (public domain).

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 (figure $6.1.1.1.a$-c). 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.

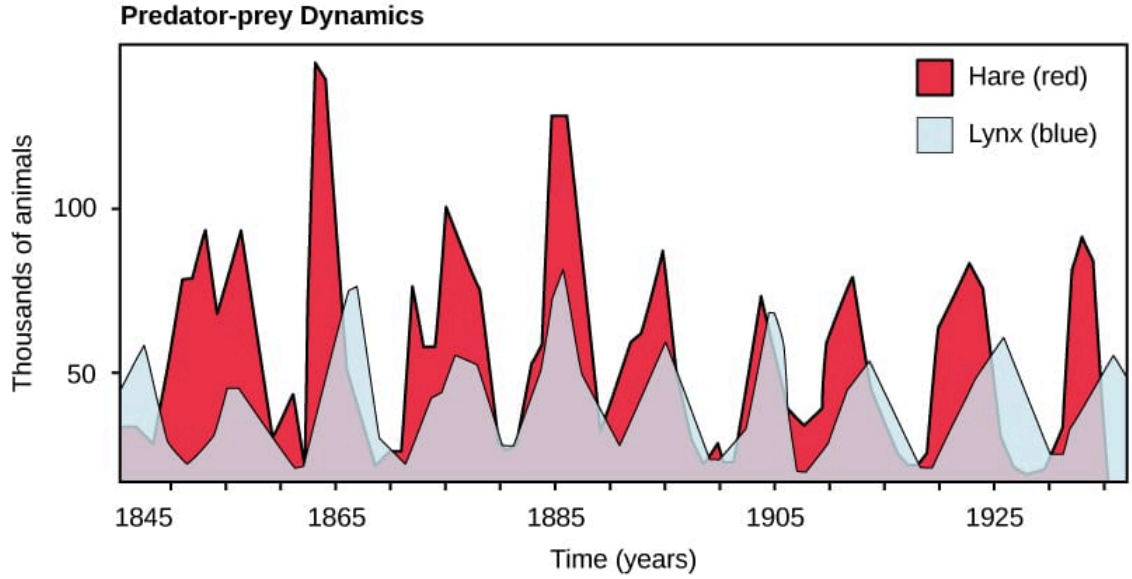

Figure $6.1.1.1.c$: The cycling of Canada lynx and snowshoe hare populations in Northern Ontario is an example of predator-prey dynamics. The x-axis shows time in years, and the y-axis shows population size in thousands of animals. The lynx population is represented in blue (shorter peaks), and the hare population is represented in red (taller peaks). Both populations increase and decrease in 10-year cycles, with changes in the lynx population lagging a few years behind that of hare.

The dynamic of closely matched population cycling occurs because the snowshoe hare is the primary food source for the lynx. When predators have generalists, feeding on a variety of prey species, and prey are consumed by a variety of predators species, their population dynamics are less likely to cycle together.

Adaptations of Predators

Predators have a variety of adaptations to catch and consume prey, and the specific adaptations depend on the predator. For example, raptors, such as owls and hawks, have hooked beaks for tearing flesh and talons for grabbing prey. Mammal predators often have sharp teeth and claws. Some predators can run quickly to chase prey, and others "sit and wait", lunging forward when prey pass them. Some predators, like rattlesnakes and tarantulas, subdue their prey by injecting them with venom (figure $6.1.1.1.d$). Predators often have large eyes located forward (like a wolf) rather than eyes spaced far apart on the sides of the head (like a sheep). Forward-facing eyes allow for depth perception, which is key to tracking prey. In contrast, peripheral vision is expanded when eyes are located to the sides, and this helps prey identify threats.

Figure 6.1.1.1.d: This Asian birdeater tarantula uses its fangs to inject its prey with poisonous venom. Image by Matt Reinbold (CC-BY-SA).

Defensive Traits in Prey

Prey evolve mechanical, chemical, physical, or behavioral defenses against predators. Some prey have armor (such as a turtle shell or the bony plates protecting armadillos), a **mechanical defense** that reduces predation by discouraging physical contact. Many animals produce or obtain **chemical defenses** from plants and store them to prevent predation. Other species use their body shape and coloration as **camouflage** to avoid being detected by predators, an example of a **physical defense**. 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 6.1.1.1.e-a). In another example, the chameleon can change its color to match its surroundings (figure 6.1.1.1.e-b).

(a) (b)

Figure 6.1.1.1.e: (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 6.1.1.1.f). 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 $6.1.1.1.f$: 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 $6.1.1.1.g$). 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 $6.1.1.1.g$: 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)

Running from predators, hiding, and playing dead are examples of **behavioral defenses**. Some prey also exhibit behaviors that threaten predators. For example, snapping turtles stretch their legs to appear larger and snap aggressively at predators.

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6.1.1.2: Herbivory

When an animal feed on parts of another organism (usually a plant), **herbivory** occurs. For example, the koala eats the eucalyptus leaves (figure $6.1.1.2.a$) or a cicada feeds a plant's sap (figure $6.1.1.2.b$). Like predators, herbivores may feed on multiple individuals over their lives; however, herbivores do not necessarily kill the plants that they eat.

Figure $6.1.1.2.a$: Koalas are herbivores that feed exclusively on eucalyptus leaves. They are thus considered specialists because the specialize on just one type of food. Image by Dr. Umesh Behari Mathur (CC-BY).

Figure $6.1.1.2.b$: This floury baker cicada feeds on plant sap by piercing the tree with needle-like mouth parts. Image by Toby Hudson (CC-BY-SA).

Plant species have evolved numerous defenses that reduce herbivory. Thorns are an example of a mechanical defense that discourages large herbivores from feeding on a plant (Figure $6.1.1.2.c$-a). Many plant species produce secondary plant compounds that serve no function for the plant except that they are toxic to animals and discourage consumption, acting as a chemical defense. For example, the foxglove produces several compounds, including digitalis, that are extremely toxic when eaten (Figure $6.1.1.2.c$-b). (Biomedical scientists have repurposed the chemical produced by foxglove as a heart medication, which has saved lives for many decades.)

(a) (b)

Figure 6.1.1.2.c: 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)

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6.1.1.3: Parasitism

Parasitism occurs when one organism (the **parasite**) takes nutrients from another (the **host**). The host is usually weakened by the parasite as it siphons resources the host would normally use to maintain itself. Parasites do not necessarily kill their hosts. When they do, it is often a slow process, allowing the parasite time to complete its reproductive cycle before it or its offspring are able to spread to another host. A parasite may remain attached to the same host for its full lifespan, but some parasites have complex life cycles involving multiple host species. For example, a tapeworm causes disease in humans when contaminated and under-cooked meat such as pork, fish, or beef is consumed. Figure $6.1.1.3.a$ illustrates the life cycle of the pork tapeworm. 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.

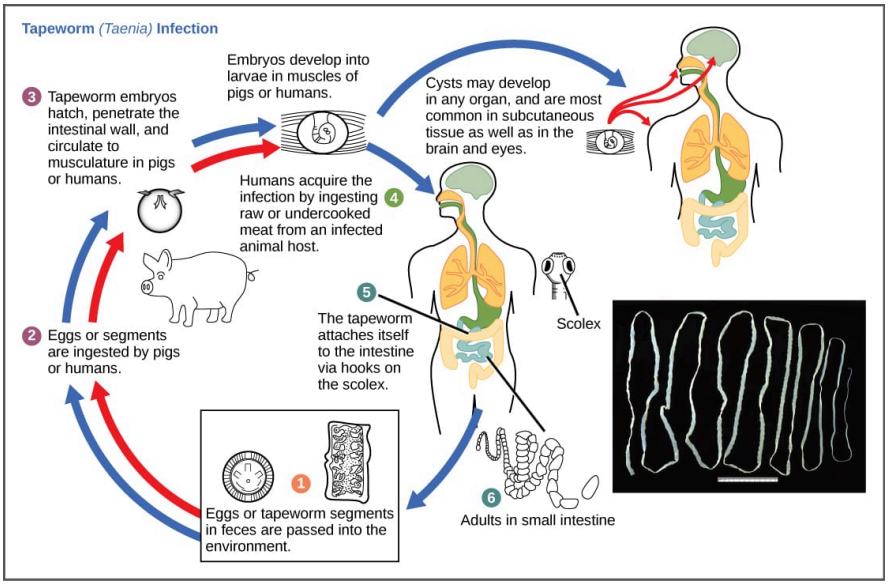

Figure $6.1.1.3.a$: This diagram shows the life cycle of the tapeworm, a human worm parasite. In the first step, eggs or tapeworm segments from human feces contaminate the environment. Second, pigs ingest these eggs or segments. Third, the eggs mature into larvae, which encyst in the muscle tissue of the pig. It is also possible for humans to develop cysts if they ingest eggs. Fourth, humans become infected when they eat pork that is undercooked. Fifth, the larvae mature into adults, attaching themselves to the intestine wall. Sixth, adult tapeworms can grow many segments and become quite long. They produce the eggs or segments that continue the life cycle. (credit: modification of work by CDC)

Parasites infect many types of organisms, including other animals and plants. For example, fleas and roundworms are common dog parasites. Plants can be infected by fungi, bacteria, and viruses; there are also plants that parasitize other plants (figure $6.1.1.3.b$). Even bacteria can be parasitized by viruses called bacteriophages.

Figure 6.1.1.3.b: Instead of conducting its own photosynthesis, the parasitic plant dodder siphons nutrients from its host plant. Image by Scot Nelson (public domain).

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6.1.1.4: Food Chains and Food Webs

Trophic interactions in a community can be represented by diagrams called **food chains** and **food webs**. Before discussing these representations in detail, we must first review the basics of energy. Energy flows through a community as a result of trophic interactions.

Energy

Virtually every task performed by living organisms requires energy. In general, **energy** is defined as the ability to do work, or to create some kind of change. Energy exists in different forms. Examples include light energy, kinetic energy, heat energy, potential energy, and chemical 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**. **Heat energy** is the energy of motion in **matter** (anything that takes up space and has mass) and is considered a type of kinetic energy. The warmer the substance, the faster its molecules are moving. The rapid movement of molecules in the air, a speeding bullet, and a walking person 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 or a person about to skydive out of an airplane (figure $6.1.1.4.a$).

Figure $6.1.1.4.a$: 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. **Chemical energy** is an example of potential energy that is stored in molecules. When molecules that are higher energy and less stable react to form products that are lower energy and more stable, this stored energy is released. Chemical energy is responsible for providing living cells with energy from food.

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 biological molecules, such as sugars (figure $6.1.1.4.b$).

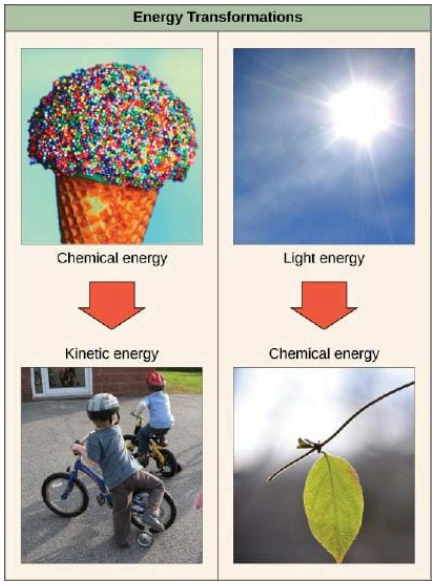

Figure $6.1.1.4.b$: Shown are some examples of energy transferred and transformed from one system to another and from one form to another. The food we consume, represented by the ice cream cone, provides our cells with the chemical energy required to carry out bodily functions. This can be converted into kinetic energy (the energy of motion), which would be needed to ride a bike. Leaves conduct photosynthesis, converting light energy from the sun to chemical energy. (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)

The challenge for all living organisms is to obtain energy from their surroundings in forms that are usable to perform cellular work. 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. 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 the metabolic reactions that occur in organisms.

The concept of order and disorder relates to the second law of thermodynamics. 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. Living things are highly ordered, requiring constant energy input to be maintained in a state of low entropy.

Energy Flow

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 (figure $6.1.1.4.c$). The energy that is harnessed from photosynthesis enters the communities 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. See the Carbon Cycle and Photosynthesis in OpenStax *Concepts of Biology* for more details about photosynthesis.

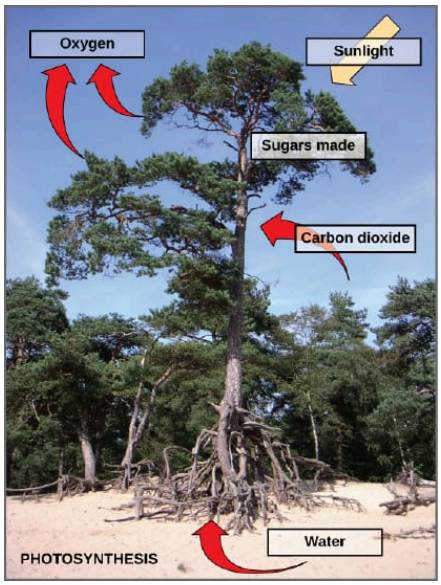

Figure $6.1.1.4.c$: Photosynthesis uses solar energy, carbon dioxide, and water to release oxygen and to produce energy-storing sugar molecules. Image and caption by OpenStax (CC-BY). Access for free at openstax.org.

Organisms that conduct photosynthesis (such as plants, algae, and some bacteria), and organisms that synthesize sugars through other means are called **producers**. Without these organisms, energy would not be available to other living organisms, and life would not be possible. **Consumers**, like animals, fungi, and various microorganisms depend on producers, 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 $6.1.1.4.d$). Using this reasoning, all food eaten by humans can be traced back to producers that carry out photosynthesis (figure $6.1.1.4.e$).

Figure $6.1.1.4.d$: 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)

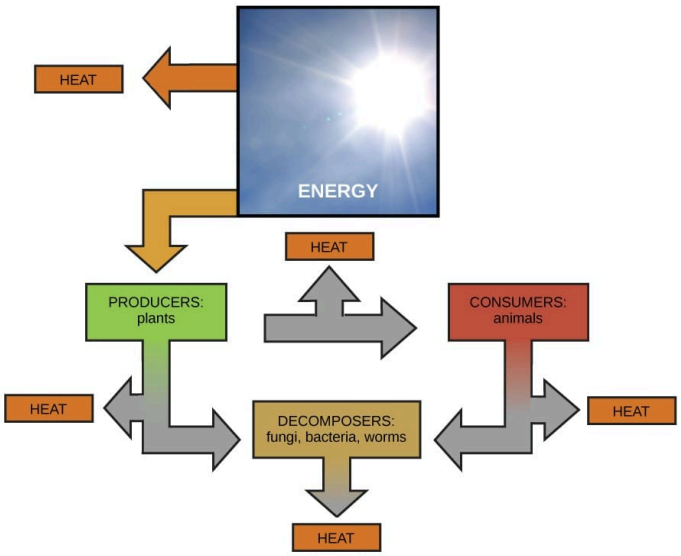

Figure 6.1.1.4.e: Ultimately, most life forms get their energy from the sun. This flow chart shows energy from the sun being captured by producers, such as plants, through photosynthesis. The energy is transferred to the consumers of the producers, such as animals. Energy can be obtained from producers directly (herbivores eat plants) or indirectly (carnivores eat herbivores). Decomposers eventually breakdown of dead organisms, including plant and animal material, and contribute to the nutrient pool. Fungi and bacteria are decomposers, and worms are detritivores (not shown). During each energy transfer, some of the energy in the system is lost as heat.

Consumers can be classified based on whether they eat animal or plant material (figure 6.1.1.4.f). Consumers that feed exclusively on animals are called **carnivores**. Lions, tigers, snakes, sharks, sea stars, spiders, and ladybugs are all carnivores. **Herbivores** are consumers that feed exclusively on plant material, and examples include deer, koalas, some bird species, crickets, and caterpillars. Herbivores can be further classified into **frugivores** (fruit-eaters), **granivores** (seed eaters), **nectivores** (nectar feeders), and **folivores** (leaf eaters). Consumers that eat both plant and animal material are considered **omnivores**. Humans, bears, chickens, cockroaches, and crayfish are examples of omnivores.

Figure 6.1.1.4.f: Carnivores like the lion (top left) eat primarily meat. The ladybug (lower left) is also a carnivore that consumes small insects called aphids. Herbivores, like the mule deer (middle) eat primarily plant material. Omnivores like the bear (top right) and crayfish (bottom right) eat both plant and animal based food. Lion by Kevin Pluck; ladybug by Jon Sullivan; mule deer by Bill Ebbesen; bear by Dave Menke; crayfish by Jon Sullivan. All from OpenStax (CC-BY). Access for free at openstax.org.

Dead producers and consumers are eaten by **detritivores** (which ingest dead tissues) and **decomposers** (which further break down these tissues into simple molecules by secreting digestive enzymes). Invertebrate animals, such as worms and millipedes, are examples of detritivores, whereas fungi and certain bacteria are examples decomposers.

Food Chains

A **food chain** is a linear sequence of organisms through which nutrients and energy pass as one organism eats another. Each organism in a food chain occupies a specific **trophic level** (energy level), its position in the food chain. The first trophic level in the food chain is the producers. The **primary consumers** (the herbivores that eat producers) are the second trophic level. Next are higher-level consumers. Higher-level consumers include **secondary consumers** (third trophic level), which are usually carnivores that eat the primary consumers, and **tertiary consumers** (fourth trophic level), which are carnivores that eat other carnivores. In the Lake Ontario food chain, shown in figure $6.1.1.4.g$, the Chinook salmon is the apex consumer at the top of this food chain. Some communities have additional trophic levels (quaternary consumers, fifth order consumers, etc.). Finally, detritivores and decomposers break down dead and decaying organisms from any trophic level. There is a single path through a food chain.

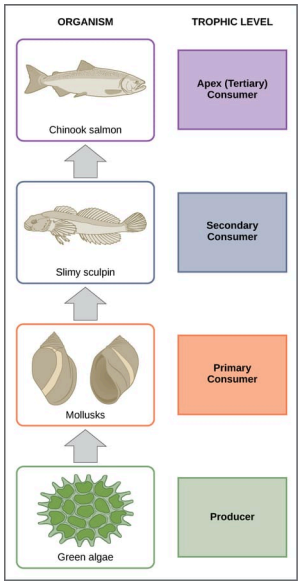

Figure $6.1.1.4.g$: These are the trophic levels of a food chain in Lake Ontario at the United States–Canada border. Energy and nutrients flow from photosynthetic green algae (producers) at the base to the primary consumers, which are mollusks, or snails. The secondary consumers are small fish called slimy sculpin. The tertiary and apex consumer is Chinook salmon. Detritivores and decomposers are not shown. (credit: modification of work by National Oceanic and Atmospheric Administration/NOAA)

One major factor that limits the number of steps in a food chain is energy. Only about 10% of the energy in one trophic level is transferred to the next trophic level. This is because much energy is lost as heat during transfers between trophic levels or to decomposers due to the second law of thermodynamics. Thus, after four to six 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 (also see Community Productivity and Transfer Efficiency).

Certain environmental toxins can become more concentrated as they move up the food chain, with the highest concentrations occurring in the top consumers, a process called **biomagnification**. Essentially, a top consumer ingests all the toxins that had previously accumulated in the bodies of the organisms at the lower trophic levels. This explains why frequently eating certain fish, like tuna or swordfish, increases your exposure to mercury, a toxic heavy metal.

Food Webs

While food chains are simple and easy to analyze, there is a one problem when using food chains to describe most communities. 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 trophic interactions, the food chain, is a hypothetical and overly simplistic representation of community 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. A **food web** is a concept that accounts for the multiple trophic interactions between each species (figure $6.1.1.4.h$ and i).

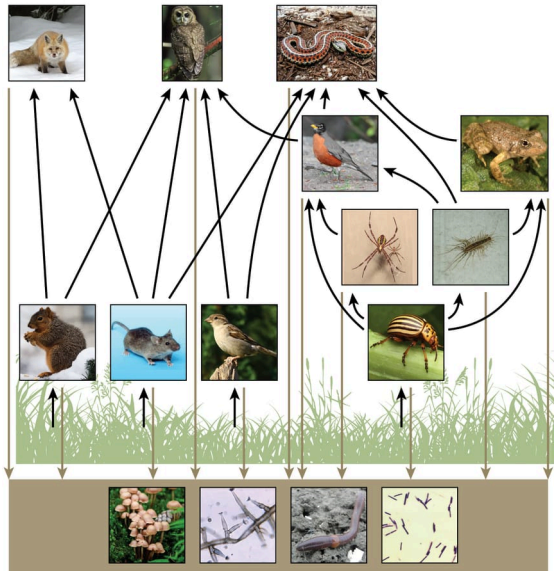

Figure 6.1.1.4.h: This food web shows the interactions among organisms across trophic levels. Arrows point from an organism that is consumed to the organism that consumes it and represent energy transfer. The producers (plants) capture energy from the sun. The level above the producers shows the primary consumers that eat the producers. Some examples are squirrels, mice, seed-eating birds, and beetles. Spiders and centipedes eat beetles. Robins eat beetles, spiders, and centipedes, and toads eat beetles and centipedes. Foxes eat squirrels and mice; owls eat squirrels, mice, seed-eating birds, and robins; and snakes eat mice, seed-eating birds, robins, centipedes, and toads. Some consumers are in between trophic levels because they eat a combination of primary, secondary, and/or tertiary consumers. All the producers and consumers eventually become nourishment for the decomposers (mushrooms, mold, and bacteria) and detritivores (earthworms) in the soil, which are depicted at the bottom of the illustration. (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)

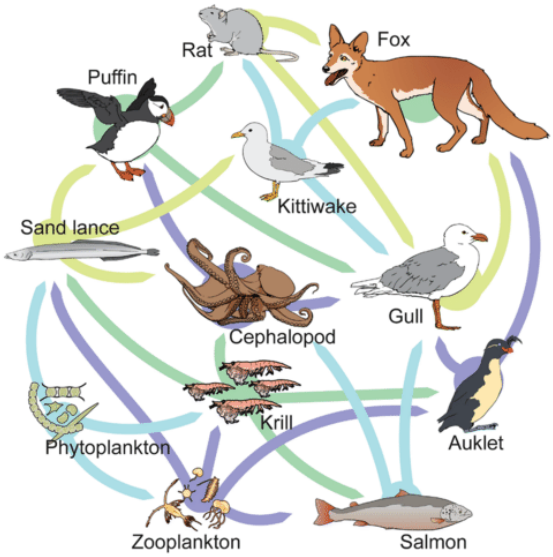

Figure 6.1.1.4.i: In this food web, each organism may have multiple food sources or be eaten by multiple species. Phytoplankton are the primary producers. They are consumed by sand lances, krill, and zooplankton. Sand lances are consumed by puffins, kittiwake, and cephalopods. Krill are consumed by the sand lance, cephalopods, auklets, and salmon. Zooplankton are consumed by the sand lance, krill, auklets, and salmon. Puffins are eaten by rats and gulls. Kittiwakes are eaten by rats, foxes, and gulls. Cephalopods are consumed by puffins and gulls. Auklets are consumed by gulls and foxes. Salmon are consumed by cephalopods and gulls. Rats are consumed by foxes and gulls. Gulls are consumed by foxes. Detritivores and decomposers are not shown. Image by Mariana Ruiz Villarreal (LadyofHats) for CK-12 Foundation (CC-BY-NC).

The trophic level of each species in a food web is not necessarily a whole number. In figure $6.1.1.4.i$, phytoplankton are the primary producers (trophic level 1). Zooplankton only feed on phytoplankton, making them primary consumers (trophic level 2). Determining the trophic level of the other species is more complex. For example, krill eat both phytoplankton and zooplankton. If krill only ate phytoplankton they would primary consumers (trophic level 2). If they ate only zooplankton, they would be secondary consumers (trophic level 3). Since, krill consume both, their trophic level is 2.5.

Community Productivity and Transfer Efficiency

The rate at which photosynthetic producers incorporate energy from the sun is called **gross primary productivity**. In a cattail marsh, plants only trap 2.2% of the energy from the sun that reaches them. Three percent of the energy is reflected, and another 94.8% is used to heat and evaporate water within and surrounding the plant. 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. At least half of the 2.2% trapped by cattail marsh plants is used to meet the plants own energy needs.

Net primary productivity is the energy that remains in the producers after accounting for the metabolic needs of the producers and heat loss. The net productivity is then available to the primary consumers at the next trophic level. One way to measure net primary productivity is to collect and weigh the plant material produced on a m^2 (about 10.7 ft^2) of land over a given interval. One gram of plant material (e.g., stems and leaves), which is largely the carbohydrate cellulose, yields about 4.25 kcal of energy when burned. Net primary productivity can range from 500 kcal/m^2/yr in the desert to 15,000 kcal/m^2/yr in a tropical rain forest.

In an aquatic community in Silver Springs, Florida, the gross primary productivity (total energy accumulated by the primary producers) was 20,810 kcal/m^2/yr (figure $6.1.1.4.j$). The net primary productivity (energy available to consumers) was only 7,632 kcal/m^2/yr after accounting for energy lost as heat and energy require to meet the producer's metabolic needs.

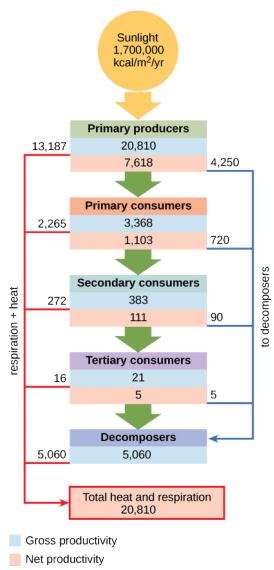

Figure $6.1.1.4.j$: The flow of energy through a spring ecosystem in Silver Springs, Florida. The gross productivity (blue) for each trophic level is listed just above the net productivity (red). Notice that the energy decreases with each increase in trophic level. The energy content of primary producers (gross productivity) is 20,810 kcal/m^2/yr. The gross productivity of primary consumers is much smaller, about 3,368 kcal/m^2/yr. The gross productivity of secondary consumers is 383 kcal/m^2/yr, and the gross productivity of tertiary consumers is only 21 kcal/m^2/yr. The net productivity of each trophic level is less than the gross productivity because some energy is used to meet metabolic needs (respiration), and some energy is lost as heat. For example, the net productivity of primary consumers was 1,103 kcal/m^2/yr, only about a third of the gross productivity. Some of the energy in each trophic level (a total of 5,060 kcal/m^2/yr) is transferred to decomposers. All of the energy initially captured by primary producers (20,810 kcal/m^2/yr) is eventually released from the system.

Only a fraction of the energy captured by one trophic level is assimilated into biomass, which makes it available to the next trophic level. Assimilation is the biomass of the present trophic level after accounting for the energy lost due to incomplete ingestion of food, energy used to conduct work by that trophic level, and energy lost as waste. Incomplete ingestion refers to the fact that some consumers eat only a part of their food. For example, when a lion kills an antelope, it will eat everything except the hide

and bones. The lion is missing the energy-rich bone marrow inside the bone, so the lion does not make use of all the calories its prey could provide. In Silver Springs, only 1103 kcal/m^2/yr from the 7618 kcal/m^2/yr of energy available to primary consumers was assimilated into their biomass. (The **trophic level transfer efficiency** between the first two trophic levels was approximately 14.8 percent.)

An animal's source of heat influences its energy needs. **Ectotherms**, such as invertebrates, fish, amphibians, and reptiles, rely on external sources for body heat, and **endotherms**, such as birds and mammals, rely on internally generated heat. Generally, ectotherms require less of the energy to meet their metabolic needs and than endotherms do, and therefore, many endotherms have to eat more often than ectotherms.

The inefficiency of energy use by endotherms has broad implications for the world's food supply. It is widely accepted that the meat industry uses large amounts of crops to feed livestock, and because a low percentage of this is assimilated into biomass, much of the energy from animal feed is lost. For example, it costs about 1¢ to produce 1000 dietary calories (kcal) of corn or soybeans, but approximately $0.19 to produce a similar number of calories growing cattle for beef consumption. The same energy content of milk from cattle is also costly, at approximately $0.16 per 1000 kcal. Thus, there has been a growing movement worldwide to promote the consumption of non-meat and non-dairy foods so that less energy is wasted feeding animals for the meat industry.

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6.1.2: Competition

Resources are often limited within a habitat and multiple species may compete to obtain them. **Competition** occurs when organisms use the same resources, and one or both organisms is harmed. Competing species are often occupy the same trophic level and compete for food, but species on different trophic levels could still compete for space, water, etc. **Intraspecific competition** occurs within a species. For example, most penguins defend territories from other individuals of the same species because they compete for suitable habitat and other resources (figure $6.1.2.a$). **Interspecific competition** occurs between different species. For example, the **invasive** vine, kudzu, competes with trees in the southeastern United States for light (figure $6.1.2.b$). Kudzu is considered invasive in this region because it occurs outside of its historical range (Asia and Australia) and causes ecological harm.

Figure $6.1.2.a$: Adélie penguins at Cape Adare in Ross Sea, Antarctica. These penguins defend small territories in which they nest. Image by Brocken Inaglory (CC-BY-SA).

Figure $6.1.2.b$: Kudzu is a vine that covers trees, shrubs, and other structures. It can fully block its competitors' access to light, eventually killing them. Image by Katie Ashdown (CC-BY).

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. Competition harms one or both competitors because it wastes energy. In an experimental test of competitive exclusion, two species of the freshwater microbe *Paramecium* were cultured separately and together. When cultured separately, both species reproduced, and the number of cells (individuals) increased. However, when the two species were grown together, one species (*P. aurelia*) grew, and the the other species (*P. caudatum*) was eliminated. Because both species occupied the same ecological niche, they could not coexist. *Paramecium aurelia* was the superior competitor in this case (figure $6.1.2.c$). Competitive exclusion may be avoided if a population evolves to make use of a different resource, a different area of the habitat, or feeds during a different time of day. This is called **resource partitioning**. The two species are then said to occupy different microniches. These species coexist by minimizing direct competition.

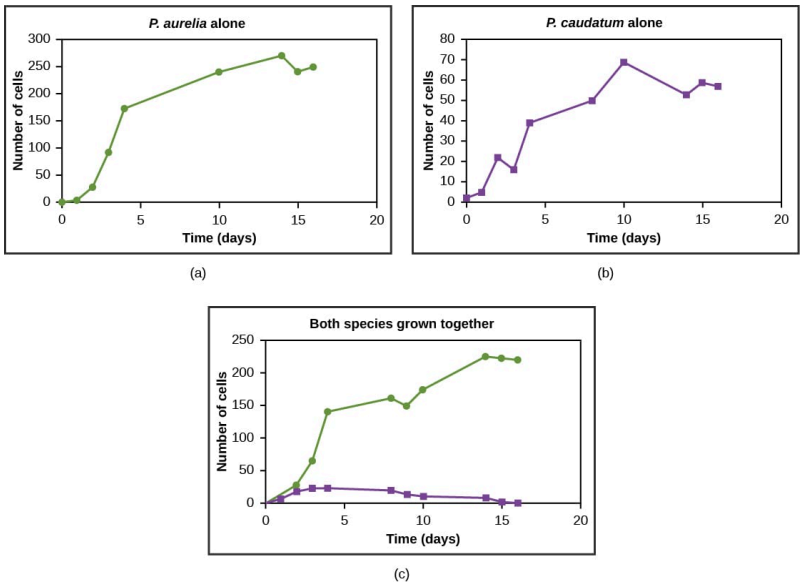

Figure $6.1.2.c$: Graphs a, b, and c all plot number of cells versus time in days. When *Paramecium aurelia* and *P. caudatum* were grown individually in the laboratory (a and b), the two species both reproduced and reached a relatively high cell density. When the two species were placed together in the same test tube (habitat, c), *P. aurelia* (top, green) reached nearly the same cell density as it exhibited when grown alone, but *P. caudatum* (bottom, purple) hardly grew at all, and eventually its population drops to zero. *Paramecium aurelia* outcompeted *P. caudatum* for food, leading to the latter's eventual extinction.

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6.1.3: Facilitation

Interactions in which one or both species benefit and neither is harmed are called facilitation. There are two types of facilitation: commensalism and mutualism.

Commensalism

Commensalism is a type of facilitation that occurs when one species benefits from an interaction, while the other neither benefits or is harmed. Many potential commensal relationships are difficult to identify because it is difficult to demonstrate that one partner is unaffected by the presence of the other. Birds nesting in trees provide an example of a commensal relationship (figure $6.1.3.a$). 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.

Figure $6.1.3.a$: 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)

Another example or a commensal relationship involves the Little Blue Heron and the White Ibis, which are both wading birds. The Little Blue Heron catches more fish in the presence of the White Ibis, but the White Ibis is unaffected. Interestingly, Little Blue Herons attempt to catch fish more often in the presence of the species, but the success rate of their attempts does not change. Nevertheless, more frequent attempts still increases the total number of fish caught. The White Ibis may make fish more visible to Little Blue Herons, causing changes in their behavior (figure $6.1.3.b$).

Figure 6.1.3.b: The Little Blue Heron (left) and the White Ibis (right) have a commensal relationship. Image by Russ (CC-BY).

Mutualism

In a **mutualism**, both species benefit from their interaction. For example, pollinators, such as bees, butterflies, and hummingbirds, benefit because they eat the collect pollen and/or nectar that they collect from flowers. The plants also benefit because their pollen is dispersed to other plants, allowing them to reproduce. Both the pollinators and the plants benefit, demonstrating a mutualism (figure 6.1.3.c). Clownfish and anemones are another example of mutualisms. Clownfish gain protection from living among anemones. In return, clownfish clean the anemones and scare away predators. In addition, their waste provides nutrients (figure 6.1.3.d).

Figure 6.1.3.c: A male Broad-Tailed Hummingbird visits a scarlet gilia flower at the Rocky Mountain Biological Laboratory. The hummingbird gains food (nectar) while aiding the gilia flower with reproduction. Image by David W. Inouye (CC-BY).

Figure $6.1.3.d$: These clownfish have a mutual relationship with the sea anemones in which they live. Image by Samuel Chow (CC-BY).

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6.1.4: Symbiosis

Some biological interactions are brief, such as predation. In others, species are closely associated for long periods. Such associations are called **symbiotic** ("living together"). One species always benefits in a symbiosis, but the other may be harmed (parasitism), unaffected (commensalism), or benefited (mutualism). Some experts considered all parasitisms, commmensalisms, and mutualisms to be symbiotic, but others only consider interactions in which species are living together in a close association (such as when one species lives on or in the other) as symbiotic.

Termites have a symbiotic relationship with microorganisms called protozoa that live in the insect's gut (figure $6.1.4.a$-a). The termite benefits from the ability of the protozoa to digest cellulose, a carbohydrate important in plant structure. However, the protozoa 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 symbiotic relationship between a fungus and algae (or a photosynthetic bacteria; Figure $6.1.4.a$-b). In lichen, the algal cells are fully surrounded by the fungus. The sugars produced by the algae through photosynthesis provide nourishment for both organisms. The physical structure of the fungus protects the algae from the elements and makes certain nutrients in the atmosphere more available to the algae. The algae of lichens can sometimes live independently given the right environment, but many of the fungal partners are unable to live on their own. Note that while both lichen and the example involving termites mutually benefit the species involved, symbioses are not always mutualisms.

Figure $6.1.4.a$: (a) Termites form a symbiotic relationship with protozoa living in their guts. Their association which allows 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)

The remora and the shark is a commensal symbiosis. The top fin of the remora is modified into a sucker with which it forms an attachment to the shark. When the shark feeds, the remora picks up scraps. Additionally, the remora gains transportation and protection. The shark makes no attempt to prey on the remora and is unaffected by it (figure $6.1.4.b$).

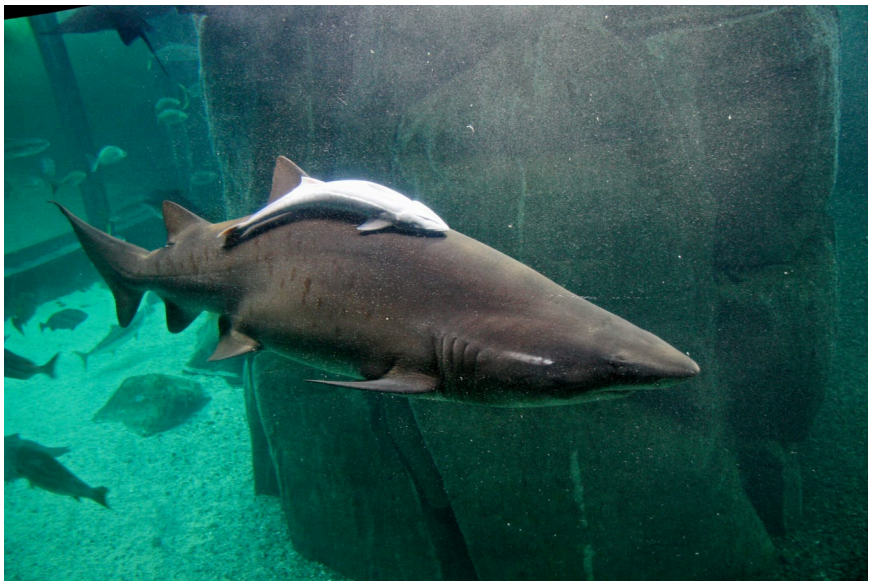

Figure $6.1.4.b$: A remora attached to the top of a shark in an aquarium. This is an example of a symbiosis because the remora lives in close association with the shark. Image by Brian Snelson (CC-BY)

There are many additional examples of symbiosis. Coral are small animals that harbor photosynthetic microorganisms called dinoflagellates. (The corals group together and deposit hardened calcium carbonate skeletons.) **Mycorrhizae** are fungi that surround or live within plant root cells and help plants absorb nutrients from the soil in exchange for sugars. In fact truffles are often found in oak forests because the fungus that produce this spore-forming body establishes mycorrhizae on oak roots. **Root nodules** are structures on the roots of legume plants that house nitrogen-fixing bacteria (see The Nitrogen Cycle). **Epiphytes** are plants adapted to live on top of other plants and are common in the tropical rainforest (see Biomes). Humans have a diversity of microorganisms, called the **normal flora**, that live in and on our bodies. While we often think of bacteria as causing infection (a parasitism), the species of our normal floral exemplify commensalism and mutualism. For example, our gut microbiota aids with digestion and helps us synthesize certain vitamins.

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6.2: Community Structure and Dynamics

Communities are complex systems that can be characterized by **community structure** (the number and size of populations and their interactions) and **community 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.

Keystone Species

A **keystone species** is one whose presence has inordinate influence in maintaining the prevalence of various species, 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 $6.2.a$). 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 $6.2.a$: Sea stars are keystone species of the intertidal zone.

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.

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 $6.2.b$) 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.

Figure $6.2.b$: During primary succession in lava on Maui, Hawaii, succulent plants are the pioneer species. (credit: Forest and Kim Starr)

The relationship between pioneer species and the more competitive (late-successional) species illustrates the complexity of biotic interactions. Pioneer species facilitate the growth of the late-successional species, and this initially appears to be a commensalism. However, the late-successional species later outcompete the pioneer species, shifting the interaction to competition.

Secondary Succession

A classic example of secondary succession occurs in forests cleared by wildfire, or by clearcut logging (figure $6.2.c$). 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.

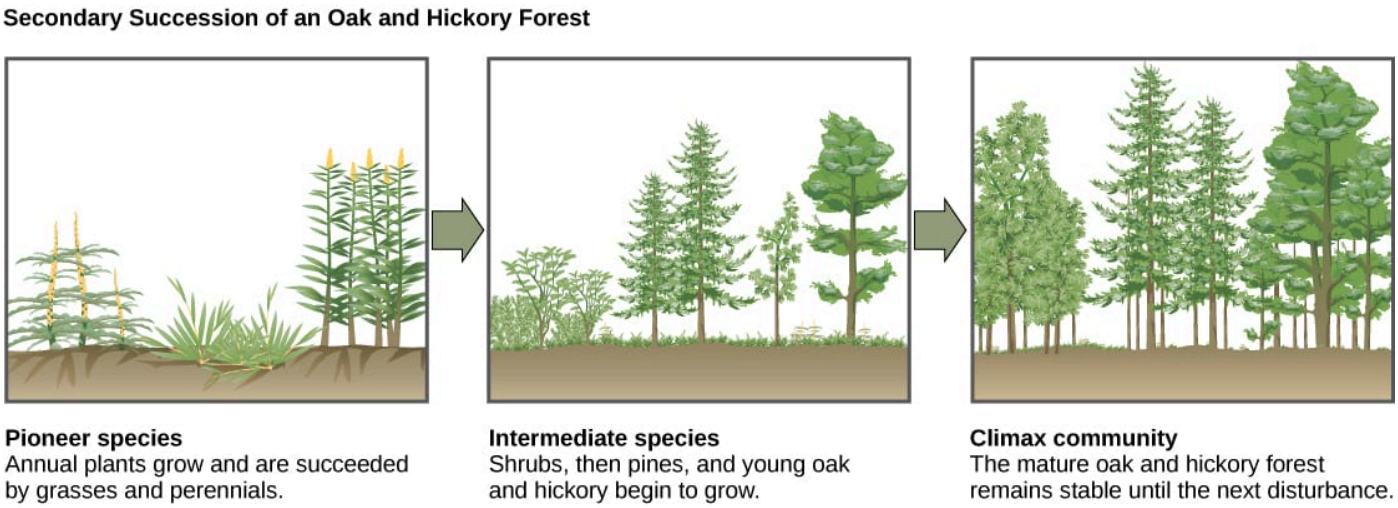

Figure $6.2.c$: Succession in an oak and hickory forest. Secondary succession occurs when a disturbance (reduction in biomass) occurs, but the entire community does not die as a result of the disturbance. First, pioneer species grow. These include annual plants, which are succeeding by perennial grasses and other perennials. Next, intermediate species, grow. These include shrubs followed by pines and young oak and hickory. Finally, the climax community is established, which consists of mature oak and hickory trees. These remain intact until the next disturbance.

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6.3: Data Dive- Bison Impacts In Prairies

Overview

In many grassland ecosystems the activities of large grazers, like bison, play a key role in shaping grassland habitat structure and diversity. A 2017 study sought to investigate how bison in tall-grass prairies affect local plant competition. Specifically, they wanted to know if bison have a positive impact on herbaceous forbs (non-woody flower species). To investigate this, they observed plant communities in tall-grass prairies in the presence and absence of bison. The two graphs below display some of the results in this study:

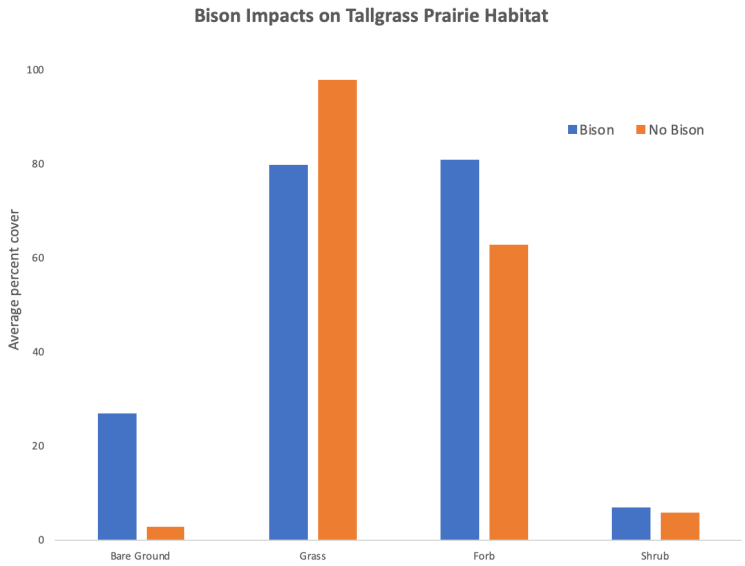

Figure $6.3.2a$: Average percent cover (aka what percent of an area a species took up) for grasses, forbs, shrubs, and bare ground in tall-grass prairies with and without bison. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Elson A and Hartnett D, 2017.

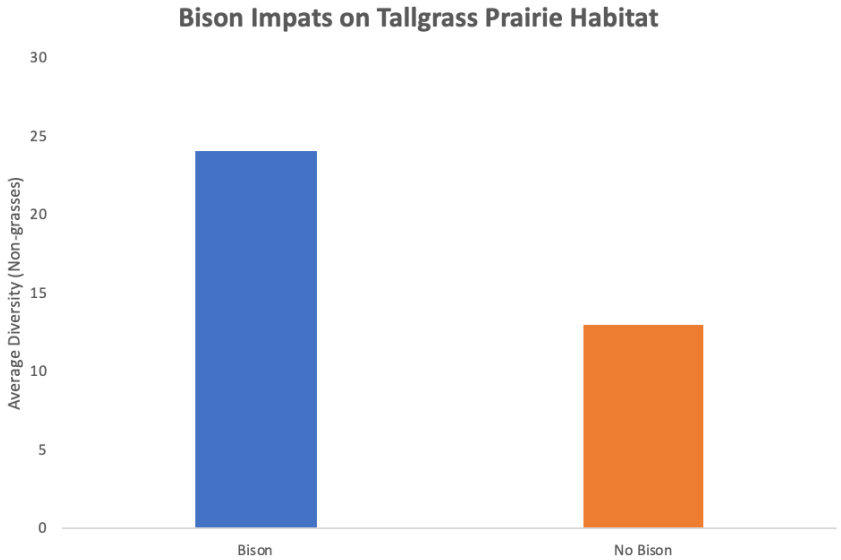

Figure $6.3.b$: Average diversity of non-grasses in tall-grass prairies with and without bison. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Elson A and Hartnett D, 2017.

Questions

1. What kind of graphs are these?
2. Does the presence of bison increase diversity? How do you know this? Which graph(s) support this?
3. How does the presence of bison affect the percent cover of bare ground, grasses, forbs, and shrubs?
4. Based on the authors objectives/predictions described above, do the results of these graphs support them? Why/why not?
5. How can we use the results of this graph to inform conservation projects for tallgrass prairies in the future?
6. What does the results of this graph make you curious about?

Raw Data From Above Graph(s)

Table $6.3.2a$**:** Raw data for average percent covers (aka what percent of an area a species took up) for grasses, forbs, shrubs, and bare ground in tall-grass prairies with and without bison. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Elson A and Hartnett D, 2017.

Status	Average Percent Cover With Bison	Average Percent Cover With No Bison
Bare Ground	27	3
Grass	80	98
Forb	81	63
Shrub	7	6

Table $6.3.b$**:** Raw data for average diversity of non-grasses in tall-grass prairies with and without bison. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Elson A and Hartnett D, 2017.

Average Diversity (Non-Grasses) With Bison	Average Diversity (Non-Grasses) With No Bison
24	13

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6.4: Review

Summary

After completing this chapter you should be able to...

- Name and distinguish among the major types of biotic interactions, providing examples of each.
- Describe how prey have adapted to reduce predation and how plants have adapted to reduce herbivory.
- Define energy and distinguish among the different types of energy.
- Explain the first and second laws of thermodynamics as they relate to trophic interactions in a community.
- Distinguish between and interpret food webs and food chains, explaining the advantages of each representation and identifying the trophic levels in each.
- Explain what limits the number of trophic levels in a community.
- Define symbiosis and provide examples.
- Explain the role of keystone species in maintaining community structure.
- Summarize the process of succession.

Communities consists of populations of different species interacting in a common area. **Biotic interactions** describe the relationships among organisms, and **trophic interactions**, including **predation**, **herbivory**, and **parasitism**, are the biotic interactions that involve one organism eating another. Trophic interactions are diagrammed through **food chains** and **food webs**.

Some biotic interactions are not trophic. For example, **competition** is a biotic interaction in which one or both organisms that use the same resources are harmed, and it can occur between individuals of the same species (**intraspecific**) or between members of different species (**interspecific**). **Facilitation** refers to interactions in which one or both species benefit and neither is harmed. Examples include **commensalism** and **mutualism**. A **symbiosis** is a close association in which species are living together.

Communities are characterized by their **structure** (number and size of populations and their interactions) and **dynamics** (how the community structure changes). **Keystone species** have a great influence on community structure, which is disproportionately large relative to their abundance. **Succession** describes how community composition changes over time following a disturbance.

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7: ECOSYSTEMS

Chapter Hook

In semi-urban areas beavers (*Castor canadensis*) are considered a nuisance as their dams block drainage pipes and cause flooding. However, in wild areas beavers are one of the most important species. Beaver dams are known for altering the flow of water. However, these dams not only slow down the movement of water, but they spread and store water in a way that is much more efficient than human-made dams. In addition, they slow and spread sediment and nutrients as they move through watersheds. What this does is create a mosaic of habitats across a landscape, both aquatic and terrestrial. More habitats lead to more species, both for plants and animals. In this way, beavers create ecosystems, one stick at a time.

Figure $7.a$ American beaver. Image by NeexPix (Public domain)

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7.1: Ecosystem Types and Dynamics

7.2: Matter

7.3: Biogeochemical Cycles

7.4: Soils

7.5: Soil Degradation

7.6: Data Dive- Beaver Impacts on Wetlands

7.7: Review

Thumbnail image - This sage thrasher's diet, like that of almost all organisms, depends on photosynthesis.

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7.1: Ecosystem Types and Dynamics

An **ecosystem** is a community of organisms (**biotic components**) 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 $7.1.a$).

(a) (b)

Figure $7.1.a$: 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)

Ecosystem Categories

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. Freshwater and marine ecosystems are found in **aquatic biomes**, which are discussed in the Biomes chapter.

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 $7.1.b$).

(a) (b)

Figure $7.1.b$: 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)

Ecosystem Dynamics

Ecosystems are complex with many interacting parts. They are routinely exposed to various **disturbances**, or changes in the environment that affect their compositions: yearly variations in rainfall and temperature and the slower processes of plant growth, which may take several years. Many of these disturbances are a result of natural processes. For example, when lightning causes a forest fire and destroys part of a forest ecosystem, the ground is eventually populated by grasses, then by bushes and shrubs, and later by mature trees, restoring the forest to its former state. The impact of environmental disturbances caused by human activities is as important as the changes caused by natural processes. Human agricultural practices, air pollution, acid rain, global deforestation, overfishing, eutrophication, oil spills, and illegal dumping on land and into the ocean are all issues of concern to conservationists.

Equilibrium is the steady state of an ecosystem where all organisms are in balance with their environment and with each other. In ecology, two parameters are used to measure changes in ecosystems: resistance and resilience. The ability of an ecosystem to remain at equilibrium in spite of disturbances is called **resistance**. The speed at which an ecosystem recovers equilibrium after being disturbed, called its **resilience**. Ecosystem resistance and resilience are especially important when considering human impact. The nature of an ecosystem may change to such a degree that it can lose its resilience entirely. This process can lead to the complete destruction or irreversible altering of the ecosystem.

Foundation Species

Foundation species are considered the “base” or “bedrock” of an ecosystem, 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 $7.1.c$). The calcium carbonate deposits of living and dead coral make up most of the reef structure, which protects many other species from waves and ocean currents.

Figure 7.1.c: Coral is the foundation species of coral reef ecosystems. (credit: Jim E. Maragos, USFWS)

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7.2: Matter

Matter is the "stuff" found in ecosystems. Technically, **matter** is defined as anything that occupies space or has mass. **Mass** is resistance to acceleration. Put more simply, mass is similar to weight, but weight accounts for acceleration due to gravity. Matter moves between biotic and abiotic ecosystem components through **biogeochemical cycles**. Fully understanding these cycles, requires a background in the particles that comprise matter, atoms.

Atoms and Molecules

Elements are substances that cannot be broken down or transformed chemically into other substances (figure $7.2.a$). A total of 118 elements have been defined; however, only 92 occur naturally and fewer than 30 are found in organisms. The remaining 26 elements are unstable and therefore do not exist for very long or are theoretical and have yet to be detected. Each element is designated by its chemical symbol (such as H, N, O, C, and Na), and possesses unique properties. These unique properties allow elements to combine and to bond with each other in specific ways.

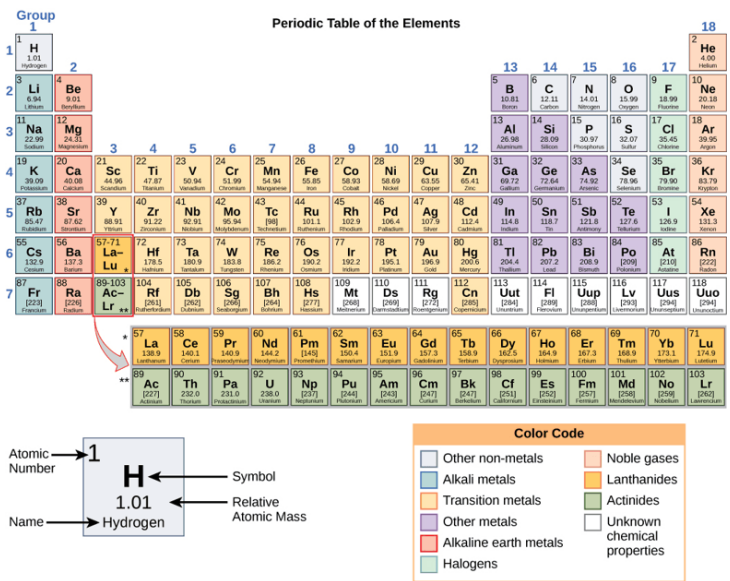

Figure $7.2.a$: The periodic table of elements organizes chemical elements based on their properties. Each element is represented by a one- or two-letter symbol. Additionally, the atomic number, name, and atomic mass are listed for each element. Click here for an accessible periodic table of elements. Image by OpenStax (CC-BY)

An **atom** is the smallest component of an element that retains all of the chemical properties of that element. For example, one hydrogen atom has all of the properties of the element hydrogen, such as it exists as a gas at room temperature and it bonds with oxygen to create a water molecule. Hydrogen atoms cannot be broken down into anything smaller while still retaining the properties of hydrogen. If a hydrogen atom were broken down into smaller particles, it would no longer have the properties of hydrogen.

All atoms contain protons, electrons, and neutrons (figure $7.2.b$). The only exception is hydrogen (H), which is typically only made of one proton and one electron. A **proton** is a positively charged particle that resides in the nucleus (the core of the atom) of an atom and has a mass of 1 and a charge of +1. An **electron** is a negatively charged particle that travels in the space around the nucleus. In other words, it resides outside of the nucleus. It has a negligible mass and has a charge of –1. **Neutrons**, like protons, reside in the nucleus of an atom. They have a mass of 1 and no charge. The positive (protons) and negative (electrons) charges balance each other in a neutral atom, which has a net zero charge.

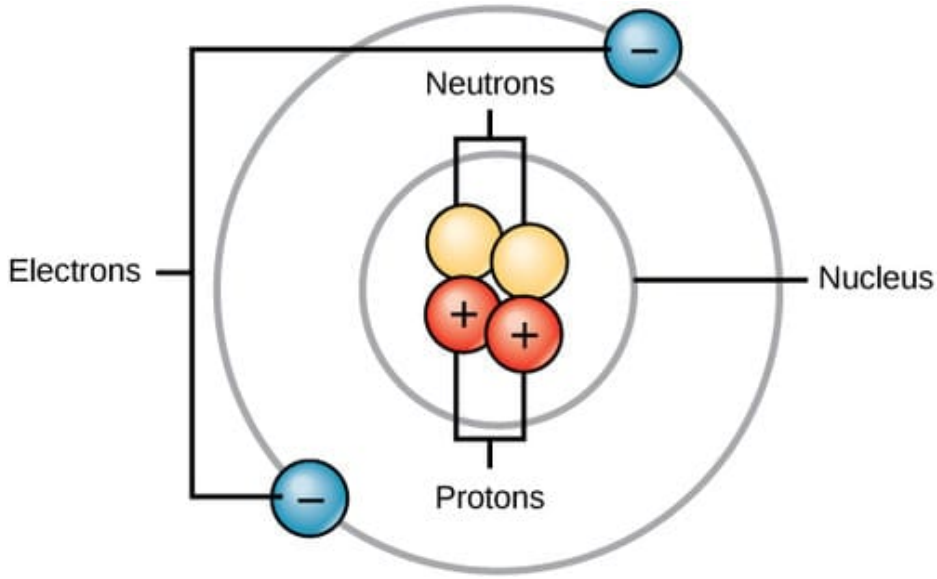

Figure $7.2.b$: Atoms are comprised of protons (red with a plus sign, +) and neutrons (yellow) located within the nucleus, and electrons (blue with a minus sign, –)surrounding the nucleus. The nucleus of an atom should not be confused with the nucleus of a cell.

Each element contains a different number of protons and neutrons, giving it its own atomic number and mass number. The **atomic number** of an element is equal to the number of protons that element contains. The **mass number** 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.

At the most basic level, all organisms are made of a combination of elements. They contain atoms that combine together to form **molecules**. Molecules are chemicals made from two or more atoms bonded together. Some molecules are very simple, like O_2, which is comprised of just two oxygen atoms. Some molecules used by organisms, such as DNA, are made of many millions of atoms.Molecules can interact to form **cells**, the structural and functional units of life. In multicellular organisms, such as animals, these cells combine to form tissues, which make up organs. These combinations continue until entire multicellular organisms are formed.

Chemical Bonds

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

Ionic and covalent bonds are strong bonds formed between two atoms. These bonds hold atoms together in a relatively stable state. **Ionic bonds** are formed between two oppositely charged ions (an anion and a cation). Because positive and negative charges attract, these ions are held together much like two oppositely charged magnets would stick together. **Covalent bonds** form when electrons are shared between two atoms. Each atom shares one of their electrons, which then orbits the nuclei of both atoms, holding the two atoms together. Covalent bonds are the strongest and most common form of chemical bond in organisms. Unlike most ionic bonds, covalent bonds do not dissociate in water. **Hydrogen bonds** form when molecules have an uneven distribution of electrons and thus have partially positive and partially negative ends. They are thus attracted to each other (figure $7.2.c$). Technically, hydrogen bonds only occur between hydrogen and either oxygen (O), nitrogen (N), or fluorine (F). Sometimes hydrogen bonds connect different parts or large molecules, as is the case in DNA and proteins. Hydrogen bonds are weaker than ionic and covalent bonds and can break easily. (Note that hydrogen bonds are among the strongest of intermolecular forces, those that occur **between** molecules, however.)

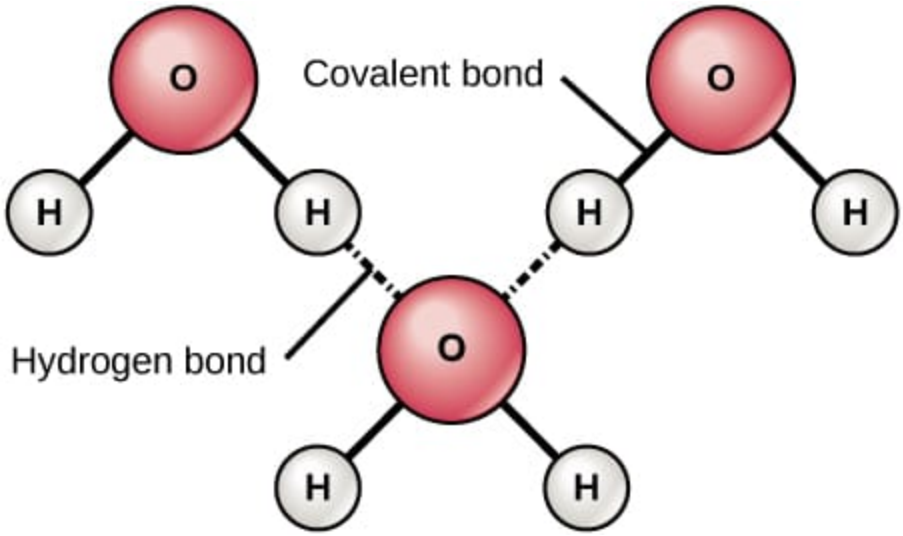

Figure 7.2.c: Hydrogen bonds form between slightly positive and slightly negative charges of certain molecules, such as water. Each water molecule consists of an oxygen atom (O) connected to two hydrogen atoms (H) by covalent bonds (solid lines). Dashed lines represent hydrogen bonds between water molecules.

Biological Macromolecules

Organisms contain large, organic molecules called **biological macromolecules**. **Organic molecules** are those that contain carbon covalently bonded to hydrogen. (In contrast, **inorganic molecules** lack carbon bonded to hydrogen and are often simpler than organic molecules.) In addition, they may contain oxygen, nitrogen, phosphorus, sulfur, and additional elements.There are four major classes of biological macromolecules: **carbohydrates**, **lipids**, **proteins**, and **nucleic acids.** Each is an important component of the cell and performs a wide array of functions.

It is often said that life is “carbon-based”. This means that carbon atoms, bonded to other carbon atoms or other elements, form the fundamental components of many of the molecules found uniquely in living things. Other elements play important roles in biological molecules, but carbon certainly qualifies as the “foundation” element for molecules in living things. It is the bonding properties of carbon atoms that are responsible for its important role. Carbon 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 7.2.d).

Carbohydrates include what are commonly referred to as simple sugars, like glucose, and complex carbohydrates such as starch. While many types of carbohydrates are used for energy, some are used for structure by most organisms, including plants and animals. For example, cellulose is a complex carbohydrate that adds rigidity and strength to the outer layer of plant cells (the cell walls).

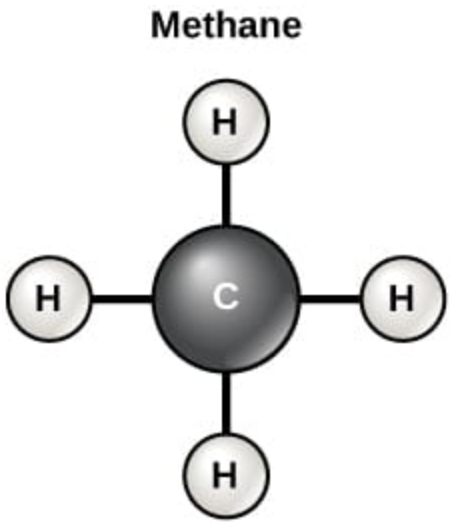

Figure $7.2.d$: Carbon can form four covalent bonds to create an organic molecule. The simplest carbon molecule is methane (CH_4), depicted here.

Lipids include a diverse group of compounds that are united by a common feature: lipids are insoluble in water. Lipids perform many different functions in a cell. Cells store energy for long-term use in the form of lipids called fats. Lipids also provide insulation from the environment for plants and animals. For example, they help keep aquatic birds and mammals dry because of their water-repelling nature. Lipids are also the building blocks of many hormones and are an important constituent of the membranes that surround cells and form many of their internal structures.

Proteins are one of the most abundant organic molecules in living systems and have the most diverse range of functions of all macromolecules. They are all polymers of amino acids. The functions of proteins are very diverse because there are 20 different chemically distinct amino acids that form long chains, and the amino acids can be in any order. Proteins can function in facilitated chemical reactions in organisms, such as photosynthesis, transmitting messages as hormones, causing muscles to contract, and much more.

Nucleic acids are very large molecules that are important to the continuity of life. They carry the genetic blueprint of a cell and thus the instructions for its functionality. The two main types of nucleic acids are deoxyribonucleic acid (**DNA**) and ribonucleic acid (RNA). DNA is the genetic material found in all organisms, ranging from single-celled bacteria to multicellular mammals. The other type of nucleic acid, **RNA**, is mostly involved in protein synthesis. DNA and RNA are made up of small building blocks known as **nucleotides**. DNA has a beautiful double-helical structure (Figure $7.2.e$).

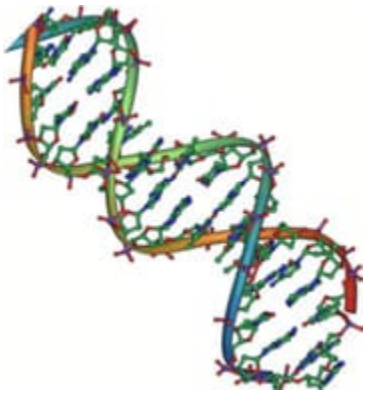

Figure $7.2.e$: The double-helix model shows DNA as two parallel strands of intertwining molecules.

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7.3: Biogeochemical Cycles

Biogeochemical cycles, also known as nutrient cycles, describe the movement of chemical elements through different media, such as the atmosphere, soil, rocks, bodies of water, and organisms. Biogeochemical cycles keep essential elements available to plants and other organisms.

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 **law of conservation of mass** states that matter is neither created nor destroyed. For example, after a chemical reaction, the mass of the products (ending molecules) will be the same as the mass of the reactants (starting molecules). The same is true in an ecosystem. Matter moves through different media, and atoms may react to form new molecules, but the amount of matter remains constant.

The biogeochemical cycles of four elements—carbon, nitrogen, phosphorus, and sulfur—are discussed below. The cycling of these elements is interconnected with the water cycle. For example, the movement of water is critical for the leaching of sulfur and phosphorus into rivers, lakes, and oceans. Today, **anthropogenic** (human) activities are altering all major ecosystems and the biogeochemical cycles they drive.

The Carbon Cycle

Carbon is the basic building block of all organic materials, and therefore, of living organisms. The carbon cycle is actually comprised of several interconnected cycles: one dealing with rapid carbon exchange among living organisms and the other dealing with the long-term cycling of carbon through geologic processes (figure $7.3.a$). 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.

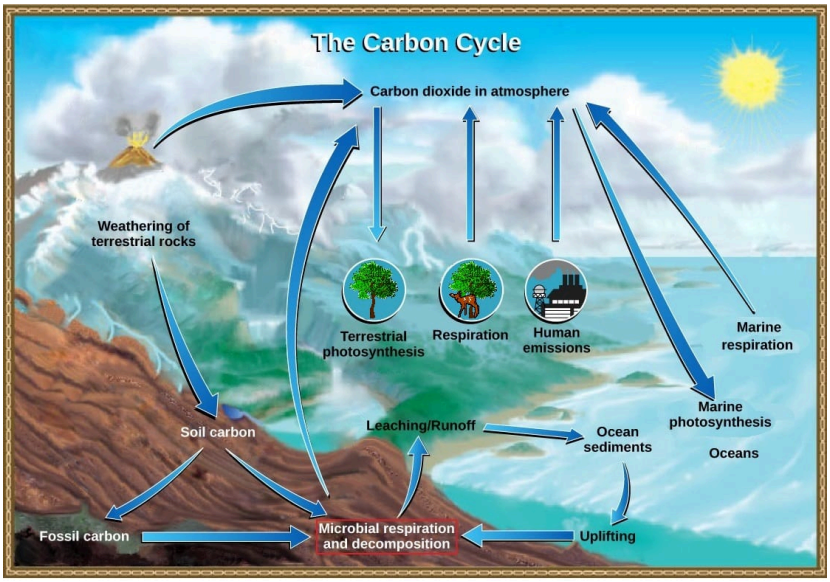

Figure $7.3.a$: Carbon dioxide in the atmosphere is converted to organic carbon through photosynthesis by terrestrial organisms (like trees) and marine organisms (like algae). Respiration by terrestrial organisms (like trees and deer) and marine organisms (like algae and fish) release carbon dioxide back into the atmosphere. Additionally, microbes that decompose dead organisms release carbon dioxide through respiration. Weathering of terrestrial rocks also brings carbon into the soil. Carbon in the soil enters the water through leaching and runoff. It can accumulate into ocean sediments and reenter land through uplifting. 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 stored carbon back into the carbon cycle. Modified from John M. Evans and Howard Perlman, USGS using tree and deer (both public domain).

Carbon Cycles Slowly between Land and the Ocean

On land, carbon is stored in soil as organic carbon in the form of decomposing organisms or terrestrial rocks. 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. The **weathering** of terrestrial rock and minerals release carbon into the soil.

Carbon-containing compounds in the soil can be washed into bodies of water through **leaching.** This water eventually enters the ocean. Atmospheric carbon dioxide also dissolves in the ocean, reacting with water molecules to form carbonate ions (CO_3^{2-}). Some of these ions combine with calcium ions in the seawater to form calcium carbonate ($CaCO_3$), a major component of the shells of marine organisms. These organisms eventually die and their shells form sediments on the ocean floor. Over geologic time, the calcium carbonate forms limestone, which comprises the largest carbon reservoir on Earth.

Carbonate also precipitates in sediments, forming carbonate rocks, such as limestone. 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. Plate tectonics can also cause **uplifting**, returning ocean sediments to land.

Carbon Cycles Quickly between Organisms and the Atmosphere

Carbon dioxide is converted into glucose, an energy-rich organic molecule through **photosynthesis** by plants, algae, and some bacteria (figure $7.3.b$). They can then produce other organic molecules like complex carbohydrates (such as starch), proteins and lipids, which animals can eat. Most terrestrial autotrophs obtain their carbon dioxide directly from the atmosphere, while marine autotrophs acquire it in the dissolved form (bicarbonate, HCO_3^-).

(a) (b) (c)

Figure $7.3.b$: (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)

Plants, animals, and other organisms break down these 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 $7.3.c$). 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 7.3.c: 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.

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 7.3.e). 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 7.3.e: 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. 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. (See Threats to Biodiversity and Climate Change for more details.)

The Nitrogen Cycle

All organisms require nitrogen because it is an important component of nucleic acids, proteins, and other organic molecules. Getting nitrogen into living organisms is difficult. Plants and algae are not equipped to incorporate nitrogen from the atmosphere (where it exists as tightly bonded, triple covalent N_2) although this molecule comprises approximately 78 percent of the atmosphere. Because most of the nitrogen is stored in the atmosphere, the atmosphere is considered a reservoir of nitrogen.

The nitrogen molecule (N_2) is quite inert. To break it apart so that its atoms can combine with other atoms requires the input of substantial amounts of energy. **Nitrogen fixation** is 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 $7.3.f$).

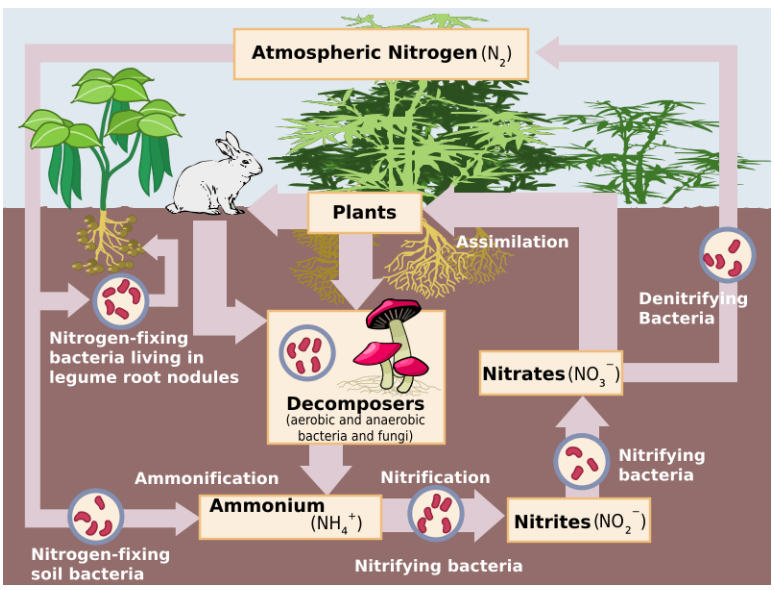

Figure $7.3.f$: In the nitrogen cycle, nitrogen-fixing bacteria in the soil or legume root nodules convert nitrogen gas (N_2) from the atmosphere to ammonium (NH_4^+). Nitrification occurs when bacteria convert ammonium to nitrites (NO_2^-) and then to nitrates (NO_3^-). Nitrates re-enter the atmosphere 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. Some form a symbiotic relationship with plants in the legume family, which includes beans, peas, soybeans, alfalfa, and clovers (figure $7.3.g$). Some nitrogen-fixing bacteria even establish symbiotic relationships with animals, e.g., termites and "shipworms" (wood-eating bivalves). Nitrogen-fixing cyanobacteria are essential to maintaining the fertility of semi-aquatic environments like rice paddies. Although the first stable product of the process is ammonia, this is quickly incorporated into protein and other organic nitrogen compounds.

Figure $7.3.g$: Nitrogen-fixing bacteria live in the spherical nodules of this soybean root. Image by United Soybean Board (CC-BY).

Ammonium is converted by bacteria and archaea into nitrites (NO_2^-) and then nitrates (NO_3^-) through the process of **nitrification**. 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.

Plants and other producers directly use ammonium and nitrates to make organic molecules through the process of **assimilation**. This nitrogen is now available to consumers. Organic nitrogen is especially important to the study of ecosystem dynamics because many processes, such as primary production, are limited by the available supply of nitrogen.

Consumers excrete organic nitrogen compounds that return to the environment. Additionally dead organisms at each trophic level contain organic nitrogen. Microorganisms, such as bacteria and fungi, decompose these wastes and dead tissues, ultimately producing ammonium through the process of **ammonification.**

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.

Human activity can alter the nitrogen cycle by two primary means: the combustion of fossil fuels, which releases different **nitrogen oxides** into the atmosphere, and by the use of artificial fertilizers in agriculture. Atmospheric nitrogen (other than N_2) is associated with several effects on Earth's ecosystems. Nitrogen oxides (HNO_3) can react in the atmosphere to form nitric acid, a form of **acid deposition**, 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) causes warming resulting in climate change.

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 $7.3.h$). 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.

Figure $7.3.h$: Fertilizer containing nitrogen is conventionally applied at large scales in agriculture. Image by Bob Nichols, USDA Natural Resources Conservation Service (public domain).

The Phosphorus Cycle

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. Phosphorus is used to make nucleic acids and the phospholipids that comprise biological membranes.

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 $7.3.i$). 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.

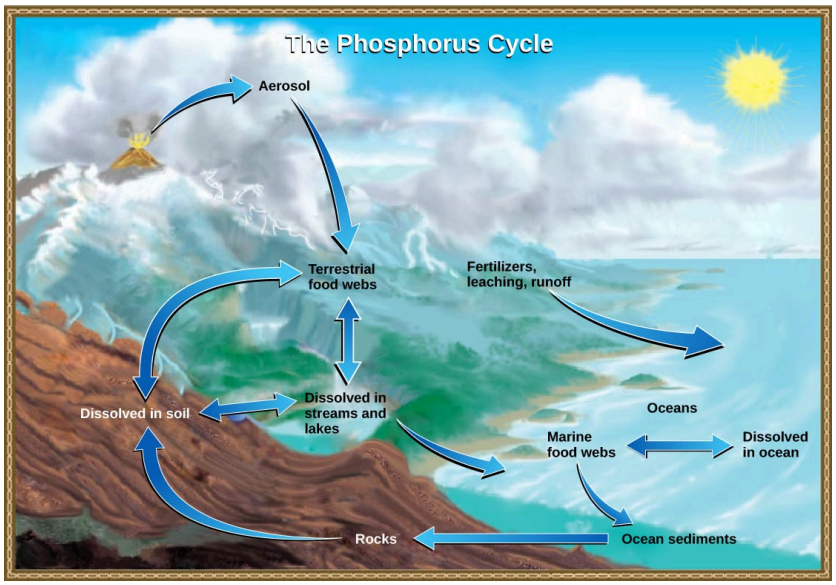

Figure 7.3.i: In nature, phosphorus exists as the phosphate ion (PO_4^{3-}). Phosphate enters the atmosphere from volcanic aerosols, which precipitate to Earth. Weathering of rocks also releases phosphate into the soil and water, where it becomes available to terrestrial food webs. Some of the phosphate from terrestrial food webs dissolves in streams and lakes, and the remainder enters the soil. Phosphate enters the ocean via surface runoff, groundwater flow, and river flow, where it becomes dissolved in ocean water or enters marine food webs. Some phosphate falls to the ocean floor where it becomes sediment. If uplifting occurs, this sediment can return to land. (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.

Eutrophication and Dead Zones

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 7.3.j). There are more than 500 dead zones worldwide. One of the worst dead zones is off the coast of the United States in the Gulf of Mexico. Fertilizer runoff from the Mississippi River basin created a dead zone, which reached its peak size of 8,776 square miles in 2017. Phosphate and nitrate runoff from fertilizers also negatively affect several lake and bay ecosystems including the Chesapeake Bay in the eastern United States.

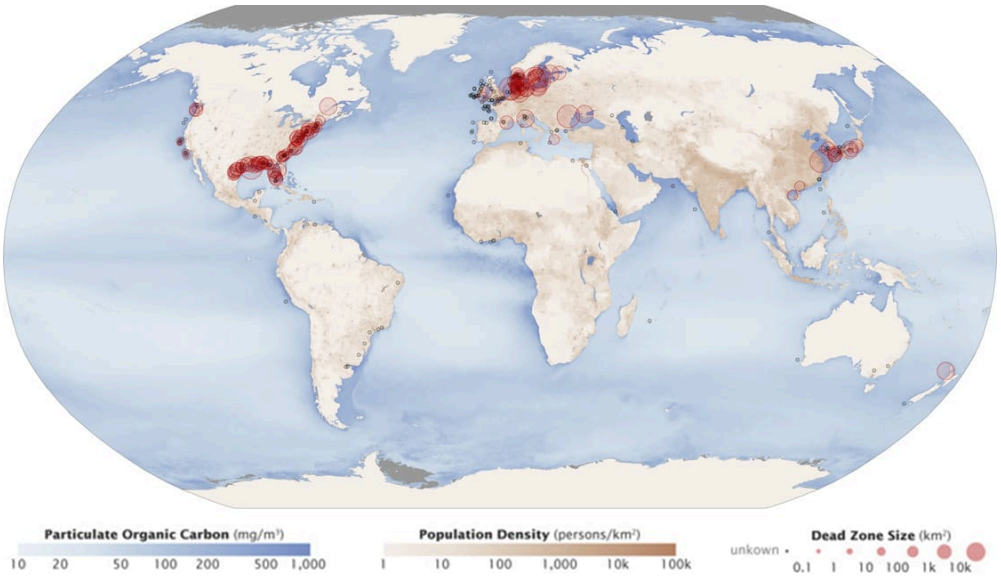

Figure $7.3.j$: Dead zones occur when phosphorus and nitrogen from fertilizers cause excessive growth of microorganisms, which depletes oxygen and kills fauna. This map shows dead zones around the world in 2008. Worldwide, large dead zones are found in coastal areas of high population density. (credit: NASA Earth Observatory)

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 $7.3.k$). 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 $7.3.k$: 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.

The Sulfur Cycle

Sulfur is an essential element for the molecules of living things. As part of the amino acid cysteine, it is critical to the three-dimensional shape of proteins. As shown in Figure $7.3.l$, sulfur cycles among the oceans, land, and atmosphere. Atmospheric sulfur is found in the form of sulfur dioxide (SO_2), which enters the atmosphere in three ways: first, from the decomposition of organic molecules; second, from volcanic activity and geothermal vents; and, third, from the burning of fossil fuels by humans.

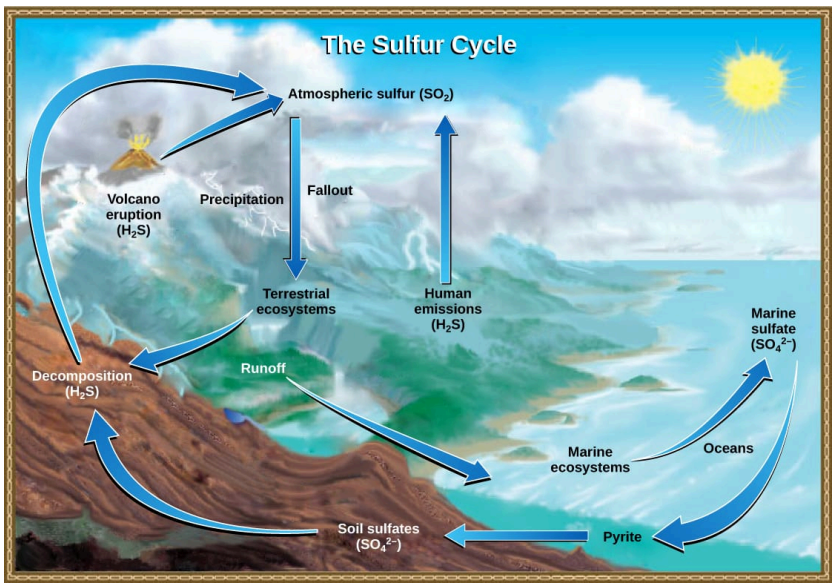

Figure $7.3.l$: The sulfur cycle. Sulfur dioxide (SO_2) from the atmosphere is dissolved in precipitation as weak sulfuric acid or falls directly to Earth as fallout. This releases sulfates (SO_4^{2-}) into the soil and water. Soil sulfates can be carried as runoff into the water. Marine sulfate can form pyrite, and this can break down to release soil sulfates. Organisms in terrestrial and marine ecosystems assimilate sulfate, adding sulfur to organic molecules, such as proteins (not shown). Decomposition of these organisms returns sulfates to the soil. Microorganisms can convert sulfates to hydrogen sulfide (H_2S) and vice versa. Decomposition, volcanic eruptions, and human activities (including burning fossil fuels) can release hydrogen sulfide (H_2S) or sulfur dioxide into the atmosphere. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

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

Sulfur enters the ocean in runoff from land, from atmospheric fallout, and from hydrothermal vents. Some ecosystems rely on microorganisms using sulfur as a biological energy source (in contrast to ecosystems with photosynthetic producers). This sulfur then supports marine ecosystems in the form of sulfates.

Human activities have played a major role in altering the balance of the global sulfur cycle. The burning of large quantities of fossil fuels, especially from coal, releases sulfur dioxide, which reacts with the atmosphere to form sulfuric acid. Like nitric acid, sulfuric acid contributes to acid deposition.

Suggested Supplementary Reading

Bruckner, M. 2018. The Gulf of Mexico Dead Zone. [Website]

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Attributions

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7.4: Soils

Soil is the outer loose layer that covers the surface of Earth. Soil quality is a major determinant, along with climate, of plant distribution and growth. Soil quality depends not only on the chemical composition of the soil, but also climate, topography, and organisms living in the soil. In agriculture, the history of the soil, such as the cultivating practices and previous crops, modify the characteristics and fertility of that soil.

Importance of Soil

Soil is important to our society primarily because it provides the foundation of agriculture and forestry. Soil plays a key role in plant growth. Beneficial aspects to plants include providing physical support, water, heat, nutrients, and oxygen. Mineral nutrients from the soil can dissolve in water and then become available to plants. Through their roots, plants absorb water and minerals (e.g., nitrates, phosphates, potassium, copper, zinc). With these and carbon dioxide acquired during photosynthesis, plants produce carbohydrates, proteins, lipids, nucleic acids, and the vitamins, on which consumers depend.

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), phosphorous (P), and sulfur (S) all pass through soil. In the hydrologic (water) cycle, soil helps to mediate **infiltration** (percolating) 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.

Several elements are considered essential for plant growth. Carbon (C), hydrogen (H), and oxygen (O) are required in large quantities, but they are not absorbed as mineral nutrients from the soil. Plants obtain carbon from carbon dioxide in the atmosphere and hydrogen from the water absorbed by the roots. Oxygen atoms come from carbon dioxide acquired during and gaseous oxygen in the atmosphere (acquire through aerobic cellular respiration) as well as water. Of the mineral nutrients absorbed from the soil, **macronutrients**, including nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), sulfur (S), and silicon (Si) are needed by plants in significant quantities. **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 chlorine (Cl), iron (Fe), boron (B), manganese (Mn), sodium (Na), zinc (Zn), copper (Cu), nickel (Ni), and molybdenum (Mo). There are some other elements that tend to aid plant growth but are not absolutely essential.

Although many aspects of soil are beneficial to plants, excessively high levels of trace metals (either naturally occurring or added by humans) or applied herbicides can be toxic to some plants (figure $7.4.a$).

Figure $7.4.a$: These native plants are affected by herbicides that were used to kill nearby weeds. Image by Matt Lavin (CC-BY-SA).

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.

An important factor affecting soil fertility is soil **pH** (the negative log of the hydrogen ion concentration). Soil pH is a measure of the acidity or alkalinity of the soil solution. On the pH scale (0 to 14) a value of seven represents a neutral solution; a value less than seven represents an **acidic** solution and a value greater than seven represents an **alkaline** solution (figure $7.4.b$). Soil pH affects the health of microorganisms in the soil and controls the availability of nutrients in the soil solution. Strongly acidic soils (less than 5.5) hinder the growth of bacteria that decompose organic matter in the soil. This results in a buildup of organic matter that has yet to be decomposed, which leaves important nutrients such as nitrogen in forms that are unusable by plants. Soil pH also affects the solubility of nutrient-bearing minerals. This is important because the nutrients must be dissolved in solution for plants to assimilate them through their roots. Most minerals are more soluble in slightly acidic soils than in neutral or slightly alkaline soils. Strongly acid soils (pH four to five), though, can result in high concentrations of aluminum, iron and manganese in the soil solution, which may inhibit the growth of some plants.

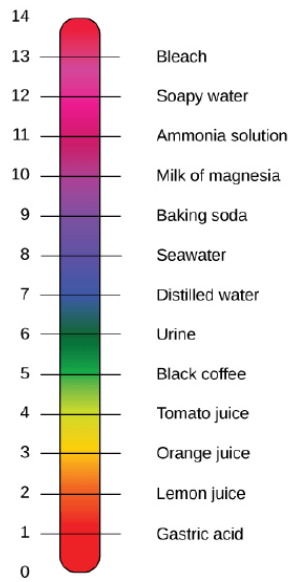

Figure $7.4.b$: The pH scale measures the amount of hydrogen ions (H^+) in a substance. This shows the pH of common household solutions. Those with a pH greater than 7 are basic (alkaline), and those with a pH less than 7 are acidic. The solutions from high to low pH are bleach (13), soapy water (12), ammonia solution (11), milk of magnesia (10), baking soda (9), seawater (8), distilled water (7), urine (6), black coffee (5), tomato juice (4), orange juice (3), lemon juice (2), and gastric acid (1). Note that pH values are approximate. Image and caption (modified) from OpenStax/Edward Stevens (CC-BY). Access for free at openstax.org.

Several factors determine soil pH. Organic material in soil decreases pH to an extent, but it also acts as a **buffer**, limiting changes in pH. Climate is also important, with high amounts of rainfall increasing leaching and lowering pH. Some types of parent material, such as those high in silicon, decrease pH, while others, such as limestone increase pH.

Soil Composition

Soil consists of organic matter (about 5%), inorganic mineral matter (40-45% of soil volume), water (about 25%) and air (about 25%). The amount of each of the four major components of soil depends on the amount of vegetation, soil compaction, and water present in the soil.

The organic material consists of dead organisms in various stages of decomposition. It is dark-colored because it contains **humus**, partially decayed matter containing organic acids. Humus enriches the soil with nutrients, gives the soil a loose texture that holds water, and allows air to diffuse through it. Oxygen is important for plant roots and many inhabitants of the soil. The organic component of soil serves as a cementing agent, returns nutrients to the plant, allows soil to store moisture, makes soil tillable for farming, and provides energy for soil microorganisms. Most soil microorganisms—bacteria, algae, or fungi—are dormant in dry soil, but become active once moisture is available.

The inorganic material of soil consists of rock, slowly broken down into smaller particles that vary in size. Soil particles that are 100 μm to 2 mm in diameter are **sand**. (A **micrometer**, μm, 10^{-6} m, or a millionth of a meter.) Soil particles between 2 and 100 μm are called **silt**, and even smaller particles, less than 2 μm in diameter, are called **clay**.

Soil should ideally contain 50 percent solid material and 50 percent pore space (figure $7.4.c$). **Pore space** refers to the gaps in between soil particles. The larger the soil particles, the larger the pore spaces. Water can quickly pass through large pore spaces, so soils high in sand drain easily. Smaller soil particles have more surface area relative to volume and produce narrow pore spaces. Water clings to these surfaces, and soils high in clay thus retain water. (Clay is also negatively charged, which attracts water.) About one-half of the pore space should contain water, and the other half should contain air.

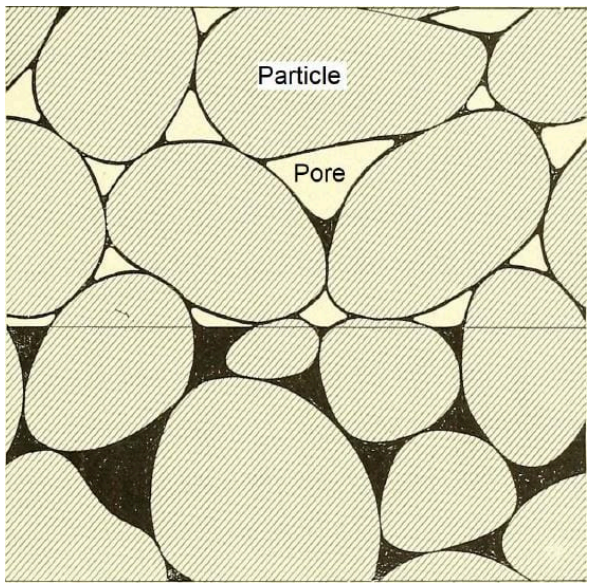

Figure $7.4.c$: Soil particles and the pore spaces in between them. The black shading represents water, which fills the pore spaces in the lower portion of the soil and clings to narrow portions of pore space in the top portion of the soil. Image from "Forest physiography; physiography of the United States and principles of soils in relation to forestry" (public domain).

Soil texture is based on percentages of sand, silt, and clay (figure $7.4.d$). Soils that have a high percentage of one particle size are named after that particle (a clay soil has a high percentage of clay). Other soils have a mixture of two particle sizes and very little of the third size. For example, silty clay has roughly 50% clay and 50% silt while sandy clay has 50-60% sand and 35-50% clay. Some soils have no dominant particle size and contain a mixture of sand, silt, and humus. These soils are called **loams**, and they are optimal for agriculture. A medium loam has roughly 40% sand, 40% silt, and 20% clay. Larger particles (sand) facilitate drainage, and small particles (clay) facilitate water retention, so loam soils both have good drainage and can remain moist. Soils that deviate slightly from a medium loam include loamy sand, sandy loam, sandy clay loam, clay loam, silty clay loam, and silty loam.

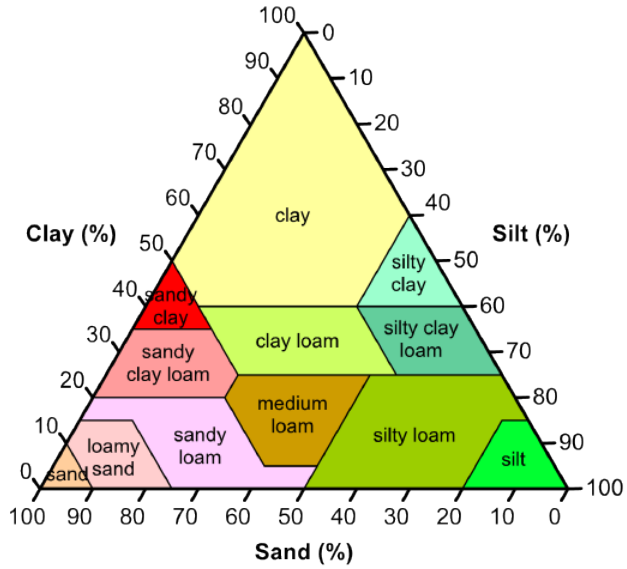

Figure $7.4.d$: A soil texture triangle is used to determine the soil texture based on the percentages of sand, silt, and clay. The left axis represents the percentage of clay. The right axis represents the percentage of silt. The bottom axis represents the percentage of sand. Most soils that contain more than 40% are classified as clays. Exceptions are silty clays, which contain 40-60% clay and 40-60% silt. Another exception are sandy clays, which contain 35-50% clay and 50-70% sand. Clay loams and silty clay loams contain 25-40% clay. Clay loams contain 20-60% silt, and silty clay loams contain 60-75% silt. Sandy clay loams contain 20-35% clay and 50-80% sand. Medium loams contain 5-25% clay, 20-50% silt, and 30-55% sand. Soils with more than 50% silt and no more than 25% clay are either silty loams or silts. Silts have 80-100% silt and no more than 15% clay. Sand have 90-100% sand. Loamy sands have 75-90% sand and no more than 15% clay. A soil with a composition that does not fit into the already described categories would be a sandy loam. To determine the soil texture, first find the percentage of clay and trace a line horizontally to the right. At the same time, find the percentage of silt and trace a line diagonally (down and to the left, parallel to the clay axis). The two lines will meet at the correct soil type. For example, traced lines from 20% clay and 40% silt intersect at the medium loam category. To confirm, trace a diagonal line (down and to the right, parallel to the sit axis) from this point to the sand axis. This line cross the axis at 40%. In summary, a line can be traced from each axis that is parallel to axis that is counterclockwise of it. Image by Richard Wheeler/Zephyris at English Wikipedia (CC-BY-SA).

Organic Versus Mineral Soils

Soils can be divided into two groups based on how they form. **Organic soils** are those that are formed from sedimentation and often contain more than 30% organic matter. They form when organic matter, such as leaf litter, is deposited more quickly than it can be decomposed (figure $7.4.e$). **Mineral soils** are formed from the weathering of rocks, typically contain no more than 30% organic matter, and are primarily composed of inorganic material. **Weathering** occurs when biological, physical, and chemical processes, such as erosion, leaching, or high temperatures, break down rocks.

Figure 7.4.e): Decomposition of organic material occurs very slowly in this acidic bog. The organic material accumulates, which is characteristic of organic soils. Image by William L. Farr (CC-BY-SA).

Soil Horizons

Soil distribution is not uniform because its formation results in the production of layers; together, the vertical section of a soil is called the **soil profile**. Within the soil profile, soil scientists define zones called horizons. A **horizon** is a soil layer with distinct physical and chemical properties that differ from those of other layers.

The soil profile has four distinct layers: 1) O horizon; 2) A horizon; 3) B horizon and 4) C horizon (figure 7.4.f-g). 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. Some soils may have additional layers (like the E horizon, figure 7.4.f), or lack one of these layers. The thickness of the layers is also variable, and depends on the factors that influence soil formation. In general, immature soils may have O, A, and C horizons, whereas mature soils may display all of these, plus additional layers.

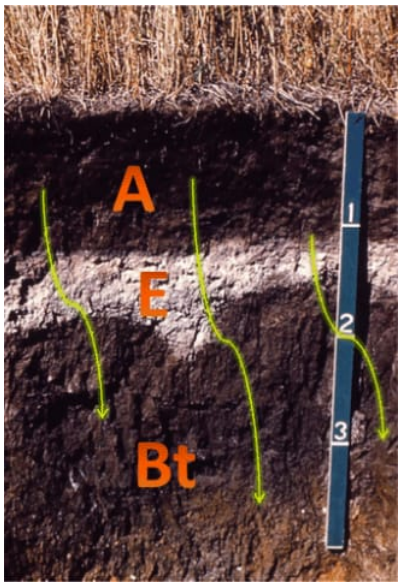

Figure 7.4.f): Soil Profile. Photograph shows a soil profile from South Dakota revealing three horizons. The A horizon (topsoil) is dark brown and extend about 1 foot. Below it is the white E (eluviated) horizon, which is about 6 inches thick. The B horizon (subsoil, labeled Bt) is the medium brown and the lowest visible layer The yellow arrows symbolize translocation of fine clays to the B horizon. The scale is in feet. Source: University of Idaho and modified by D. Grimley.

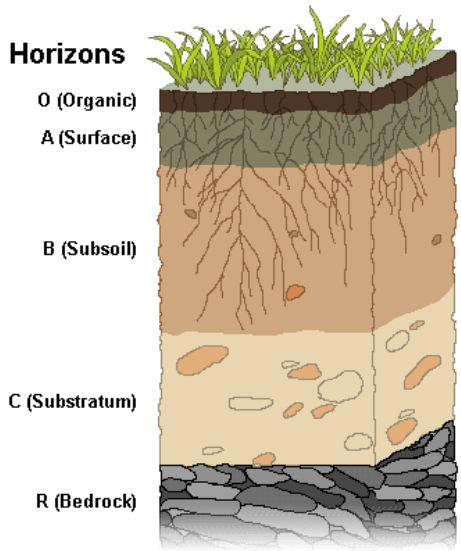

Figure 7.4.g): This image shows the different horizons, or layers, in soil. Vegetation grows at the surface. The top, deep brown layer is the O (organic) horizon. Below this is the gray A horizon (topsoil, or surface). Next is the light brown B horizon (subsoil). The C horizon (substratum, or soil base) is tan and includes larger pieces of rocks. The gray bedrock is the deepest layer. The E (eluviated) horizon that is sometimes found between the A and B horizons is absent here. This work by Wilsonbiggs is licensed under CC BY-SA 4.0

O horizon

The very top of the **O horizon** consists of partially decayed organic debris like leaves. This horizon is usually dark in color because of humus.

A horizon

The **A horizon** (topsoil) consists of a mixture of organic material with inorganic products of weathering, and it is therefore the beginning of true mineral soil. In this area, rainwater percolates through the soil and carries materials from the surface. The A horizon may be only 5 cm (2 in.), or it may over a meter. For instance, river deltas like the Mississippi River delta have deep layers of topsoil. Microbial processes occur in the top soil, and this horizon supports plant growth. Many organisms, such as earthworms and insects live among the plant roots in this horizon.

B horizon

The **B horizon** (subsoil) consists of small particles that have moved downward, resulting in a dense layer in the soil. In some soils, the B horizon contains nodules or a layer of calcium carbonate. The subsoil is usually lighter in color than topsoil and often contains an accumulation of minerals.

C horizon

The **C horizon** (soil base), includes the **parent material**, the organic and inorganic substances from which soils form. Weathering parent material represents the first steps in the chemical breakdown of rock into soil. Often the weathered parent material is underlain by the parent material itself, although in some places it has been carried from another location by wind, water, or glaciers. Beneath the C horizon lies bedrock. The chemical nature of the parent material, whether granite, limestone, or sandstone, for example, has a great influence on the fertility of the soil derived from it.

Factors Affecting Soil Formation and Composition

The fundamental factors that affect soil genesis can be categorized into five elements: climate, organisms, topography, 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.

Climate

The role of climate in soil development includes aspects of temperature and precipitation. Soils in very cold areas with permafrost conditions (such as the arctic tundra) tend to be shallow and weakly developed due to the short growing season. In warm, tropical climates, soils tend to be thicker (but lacking in organic matter), with extensive leaching and mineral alteration. In such climates, organic matter decomposition and chemical weathering occur at an accelerated rate. The presence of moisture and nutrients from weathering will also promote biological activity: a key component of a quality soil. See the Biomes chapter for more details about the effect of climate on soils.

Ancient soils, sometimes buried and preserved in the subsurface, are referred to as **paleosols** (figure $7.4.h$) and reflect past climatic and environmental conditions.

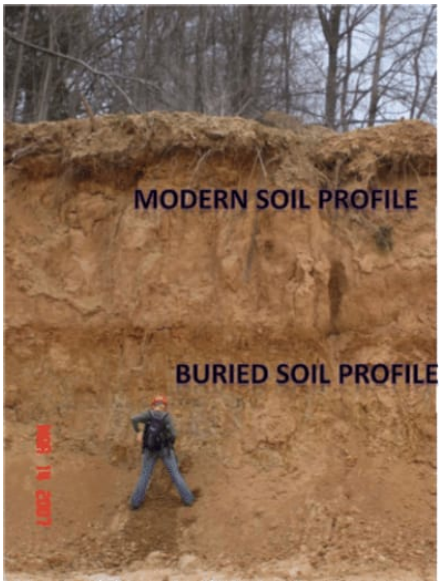

Figure $7.4.h$: Modern versus Buried Soil Profiles. A buried soil profile, or paleosol (above geologist ‘s head), represents soil development during the last interglacial period. A modern soil profile (Alfisol) occurs near the land surface. Source: D. Grimley.

Organisms

The presence of living organisms in the soil (**soil biota**) greatly affects soil formation and structure. A diversity of animals are found in the soil such as nematodes, spiders, insects, centipedes, millipedes, pillbugs, slugs, and earthworms (figure $7.4.i$). The soil also contains microorganisms like bacteria, archaea, fungi, and "protists". Animals and microorganisms can produce pores and crevices, and plant roots can penetrate into crevices to produce more fragmentation. Additionally, leaves and other material that fall from plants decompose and contribute to soil composition. Microorganisms not only decompose organic matter, but contribute to other processes in nutrient cycles, such as nitrogen fixation.

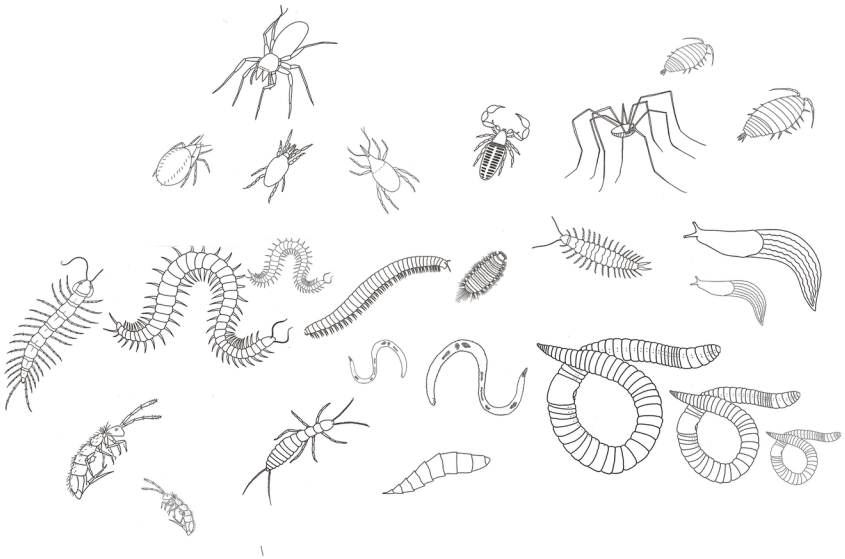

Figure 7.4.i: Illustration of animals commonly found in the soil. Image by Arne Hendriks (CC-BY)

Parent Material

Mineral soils form directly from the weathering of bedrock, the solid rock that lies beneath the soil, and therefore, they have a similar composition to the original rock. Other soils form in materials that came from elsewhere, such as sand and glacial drift. Materials located in the depth of the soil are relatively unchanged compared with the deposited material. Sediments in rivers may have different characteristics, depending on whether the stream moves quickly or slowly. A fast-moving river could have sediments of rocks and sand, whereas a slow-moving river could have fine-textured material, such as clay.

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.

Topography

Regional surface features (familiarly called “the lay of the land”) can have a major influence on the characteristics and fertility of a soil. Topography affects water runoff, which strips away parent material and affects plant growth. Soils on steep slopes are more prone to erosion and may be thinner than soils that are on relatively level ground. **Infiltration**, the percolating of water through the soil, is limited in steep soils.

The local topography can have important microclimatic effects. 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 and thicker soils because extensive root systems stabilize the soil and reduce erosion (figure 7.4.j).

Figure 7.4.j: A north-facing slope (left) and south-facing slope (right) in the Mediterranean climate (chaparral) of the Santa Monica Mountains, California. Vegetation on the north-facing slope is denser due to cool, moist conditions relative to the south-facing slope. Image by Noah Elhardt (CC-BY).

Time

Time is an important factor in soil formation because soils develop over long periods. Soil formation is a dynamic process. Materials are deposited over time, decompose, and transform into other materials that can be used by living organisms or deposited onto the surface of the soil.

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. Over time, as weathering processes deepen, mix, and alter the soil, the parent material becomes less recognizable as chemical, physical, and biological processes take effect. **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 such as landslides, glacier advance, or the rising of shorelines can rapidly bury soils. Erosion in rivers and shorelines can cause removal or truncation of soils, and wind or flooding slowly deposit sediment that adds to the soil. Animals can mix the soil and sometimes cause **soil regression**, a reversal or "bump in the road" for the normal path of development, and this increases development over time.

Soil Taxonomy

Soils are classified into one of 12 soil orders based on soil horizons, how they form, and their chemical compositions. For example, Mollisols (figure 7.4.f), which are found in temperate grasslands, have a thick topsoil rich in organic content. Aridisols, on the other hand, are dry soils that contain calcium carbonate and are found in deserts. Each soil order is further divided into suborders. See USDA's The Twelve Orders of Soil Taxonomy and The Twelve Soil Orders from the University of Idaho for more details.

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7.5: Soil Degradation

Once fertile topsoil is lost, it is not easily replaced. **Soil degradation** refers to deterioration in the quality of the soil and the resultant reduction in its capacity to produce. Soils are degraded primarily by erosion, compaction, and salinization. Such processes often arise from poor soil management during agricultural activities. In extreme cases, soil degradation can lead to **desertification** (conversion of land to desert-like conditions) of croplands and rangelands in semi-arid regions. See the Sustainable Agriculture section for strategies to preserve soil quality (**soil conservation**).

Erosion

Erosion is the biggest cause of soil degradation. Soil productivity is reduced as a result of losses of nutrients, water holding capacity, and organic matter. **Water holding capacity** is a measure of of the soils ability to retain water. The two agents of erosion are wind and water, which act to remove the finer particles from the soil. **Wind erosion** occurs mostly in flat, dry areas and moist, sandy areas along bodies of water. Wind not only removes soil, but also dries and degrades the soil structure. **Water erosion** is the most prevalent type of erosion. It occurs when raindrops splash on the ground and when water moves down slope as a thin film, small streams, or a large stream.

Some amount of soil erosion is a natural process along sloping areas and/or in areas with soft or materials that do not stick together and are susceptible to movement by water, wind, or gravity. For instance, soil material can be mobilized in strong windstorms, along the banks of rivers, in landslides, or by wave action along coastlines. However, human activities such as construction, logging, and off-road vehicle use promote erosion by removing the natural vegetation cover protecting the soil. Agricultural practices such as overgrazing and leaving plowed fields bare for extended periods contribute to farmland erosion. Each year, an estimated two billion metric tons of soil are eroded from farmlands in the United States alone. The soil transported by the erosion processes can also create problems elsewhere (for example, by clogging waterways and filling ditches and low-lying land areas). The areas most vulnerable to soil erosion include locations with thin organic (A and O) horizons and hilly terrains (figure $7.5.a$).

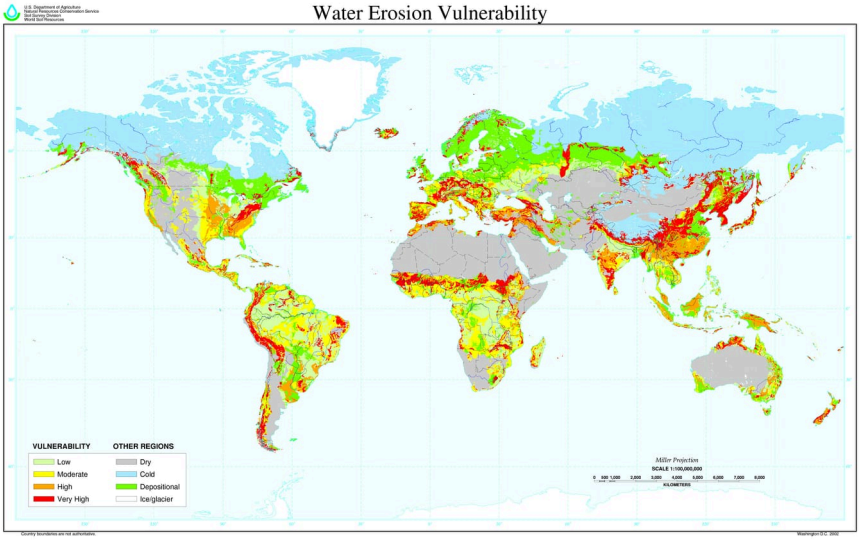

Figure $7.5.a$: Global map of water erosion vulnerability. There are four levels of vulnerability: very high (red), high (orange), moderate (yellow), and low (light green). Examples of regions with very high vulnerability to erosion by water include the west coast of South America, parts of the eastern United States, regions around the Mediterranean Sea, a strip across western and central Africa, Korean and Japan, Northern Australia, and New Zealand. Examples of regions with low vulnerability include northern South America, the Democratic Republic of Congo, northern India and Nepal, and western Russia. Other regions are labeled as dry (gray), cold (light blue), depositional (bright green), or ice/glacier (white). For example, northern regions are cold and ice/glacier. Much of the western United States, Chile and Argentina, northern Africa, the Middle East, Kazakhstan, Mongolia, and much of Australia are considered dry. The largest depositional area (region where sediments accumulate) is northeastern Europe. Image by USDA-NRCS, Soil Science Division, World Soil Resources (public domain).

Compaction

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 biota. Much compaction is reversible and some is unavoidable with modern practices; however, serious compaction issues can occur when the equipment is used excessively during times when the soil has a high water content. The problem with soil compaction is that increased soil density limits root penetration depth and may inhibit proper plant growth.

Salinization

When considerable quantities of salt accumulate in the soil in a process known as **salinization**, many plants are unable to grow properly or even survive. This is especially a problem in irrigated farmland. Groundwater used for irrigation contains small amounts of dissolved salts. Irrigation water that is not absorbed into the soil evaporates, leaving the salts behind. This process repeats itself and eventually severe salinization of the soil occurs. A related problem is water logging of the soil. When cropland is irrigated with excessive amounts of water in order to leach salts that have accumulated in the soil, the excess water is sometimes unable to drain away properly. In this case it accumulates underground and causes a rise in the subsurface water table. If the saline water rises to the level of the plant roots, plant growth is inhibited.

Desertification

Land that was previously suited for growing crops may be turned into desert by climate change and the activities of humans, such as poor farming practices, livestock overgrazing, and overuse of available water. This process, called **desertification**, is a serious problem worldwide. Plants and soil types that are non-arid (not dry) specifically help water soak into the ground (infiltration) and water retention. When desertification begins, it leads to a reduction in vegetation and degraded soil quality, and this further increases the aridity and spreads the desert via a **positive feedback loop** (meaning that the processes feed on themselves promoting an increasing spiral).

Figure $7.5.b$ shows areas of the world and their vulnerability to desertification. Note the red and orange areas in the western and midwestern United States. The Dust Bowl of the 1930s is a classic example of human-caused desertification (figure $7.5.c$). Poor cultivation and grazing practices -- coupled with severe drought conditions -- led to severe wind erosion of soil in a region of the Great Plains that became known as the "Dust Bowl". Wind stripped large areas of farmlands of topsoil, and formed clouds of dust that traveled as far as the eastern United States.

Sometimes there is a conflict between what is known to prevent desertification and what an individual farmer feels is needed to do to make a living. Mitigating the desertification process includes both societal steps and individual education on alternatives.

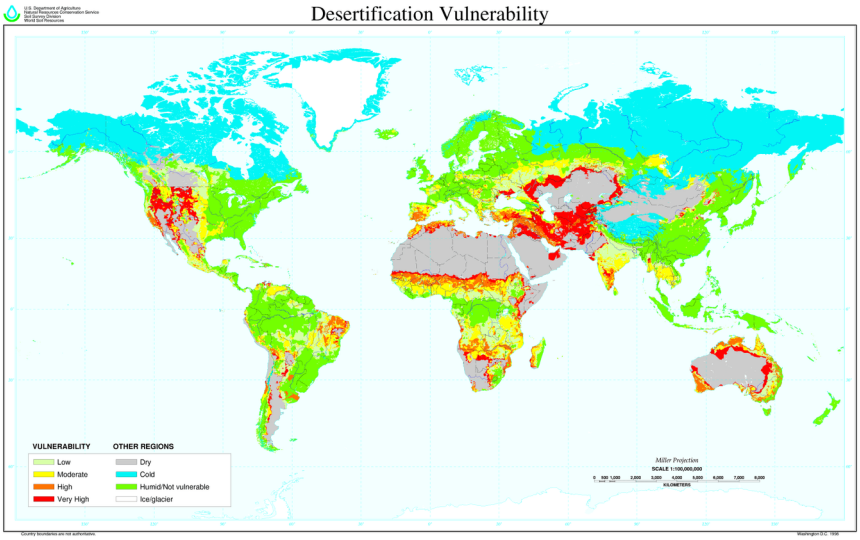

Figure $7.5.b$: World map showing desertification vulnerability. There are four levels of vulnerability: very high (red), high (orange), moderate (yellow), and low (light green). Examples of regions with a very high vulnerability to desertification include the northwestern United States, a strip through western and central Africa, parts of the middle East, and parts of Australia. Examples of regions with low vulnerability include parts of Canada, parts of western Europe, and parts of Angola and the Democratic Republic of Congo. Other regions are labeled as dry (gray), cold (light blue), humid/not vulnerable (bright green), or ice/glacier (white). For example, northern regions are cold and ice/glacier. Some of southwestern United States, Chile and Argentina, northern Africa, the Middle East, Kazakhstan, Mongolia, and much of Australia are considered dry. Examples of humid/not vulnerable areas include the eastern United States, northern and eastern South America, western Europe, Central Africa, and East Asia. Image by USDA (public domain).

Figure $7.5.c$: A cloud of dust in Kansas in 1935, part of the Dust Bowl. Image by NOAA Photo Library (public domain).

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7.6: Data Dive- Beaver Impacts on Wetlands

Overview

An ecosystem engineer is any animal that creates, significantly modifies, maintains or destroys a habitat. These organisms impact both the abiotic and biotic components of a habitat and can thus completely change landscapes. One 2017 study sought to understand if beavers (classic ecosystem engineer) could even be used as a tool for habitat restoration of wetlands. Specifically, this study focused on quantifying if wetland biodiversity improved as a result of reintroducing beavers on a landscape degraded by agriculture. Figure 2.4.6a below displays some of the results in this study:

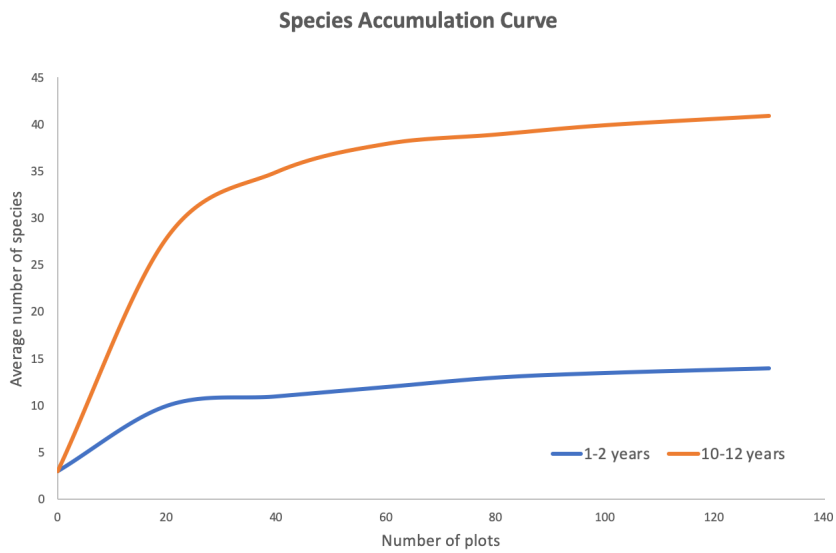

Figure $7.6.a$: Average number of species observed in sample plots 1-2 years and 10-12 years after beavers were introduced. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Law A, Graywood MJ, Jones KC, Ramsay P, and Willby NJ 2017.

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph?
3. What trend(s) can be observed in this graph between the 1-2 and 10-12 timetables? Support your answer by referring to appropriate patterns in the graph.
4. Do you think like the authors are satisfied with the results in the graph? Why?
5. How can the results of this graph to inform future reintroduction of beavers where wetland restoration is needed?
6. What information/patterns is not clear from this graph?

Raw Data From Above Graph(s)

Table $7.6.a$**:** Raw data for average number of species observed in sample plots 1-2 years and 10-12 years after beavers were introduced. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Law A, Graywood MJ, Jones KC, Ramsay P, and Willby NJ 2017.

Number Of Plots	Average Number Of Species After 1-2 Years	Average Number Of Species After 10-12 Years
0	3	3
20	10	28

Number Of Plots	Average Number Of Species After 1-2 Years	Average Number Of Species After 10-12 Years
40	11	35
60	12	38
80	13	39
100	13.5	40
130	14	41

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7.7: Review

Summary

After completing this chapter you should be able to...

- Differentiate between abiotic and biotic ecosystem components.
- Describe the three main categories of ecosystems.
- Explain the law of conservation of mass.
- Discuss the biogeochemical cycles of carbon, nitrogen, phosphorus, and sulfur.
- Explain how human activities have impacted these cycles and the potential consequences for Earth.
- Explain how soil characteristics influence plant growth.
- Identify and describe each component of soil.
- Distinguish among sand, silt, and clay and explain how particle size influences soil texture.
- Describe each horizon in a typical soil profile.
- Explain how soils are formed, describing each of the five major factors that affect soil formation and composition.
- Describe the major types and causes of soil degredation.

Ecosystems consist of living (**biotic**) and nonliving (**abiotic**) components. They can be classified as freshwater, marine, or terrestrial. **Resistance** and **resilience** are measures of ecosystem health.

Matter is anything that occupies space and has mass. Pure forms of matter are called **elements** and the smallest units of an element are **atoms**. Atoms form molecules through **ionic, covalent,** or **hydrogen bonding**. Molecules that contain carbon and hydrogen covalent bonds are called **organic**. There are four main type of large organic molecules (**biological macromolecules**) in organisms: carbohydrates, lipids, proteins, and nucleic acids.

The chemical elements that organisms need continuously cycle through ecosystems. Cycles of matter are called **biogeochemical cycles,** or **nutrient cycles**, because they include both biotic and abiotic components and processes. Examples of biogeochemical cycles include the carbon, nitrogen, phosphorus, and sulfur cycles, and each of these can be altered through human activities.

Soil consists of organic and inorganic material as well as water and air. The organic material of soil is made of **humus**, which improves soil structure and provides nutrients. Soil inorganic material consists of rock slowly broken down into smaller particles that vary in size, such as sand, silt, and loam. Soils form slowly as a result of biological, physical, and chemical processes. Soil is not homogenous because its formation results in the production of layers called a **soil profile**. Most soils have four distinct **horizons,** or layers: O, A, B, and C. Their composition is influenced by the climate, presence of living organisms, topography, parent material, and time. The processes of erosion, compaction, and desertification degrade soils. While these processes occur naturally to an extent, they are exacerbated by certain agricultural practices, deforestation, and other human activities.

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8: BIOMES

Chapter Hook

At the North Pole there is nothing but ice and snow. The taiga (also known as the boreal forest) is the northernmost place that trees can grow. At first, trees are very sparse and stunted. Sometimes these trees can take upwards of 50 years to get bigger than a seedling. Eventually, the taiga turns into a sea of trees. There are as many trees here as in all rainforests combined, representing nearly a third of all trees on Earth. As such, the taiga is the largest carbon sink on land and contributes significantly to the contribution of oxygen in the atmosphere. The taiga is just one of Earths biomes, each is unique and extraordinary in their own ways.

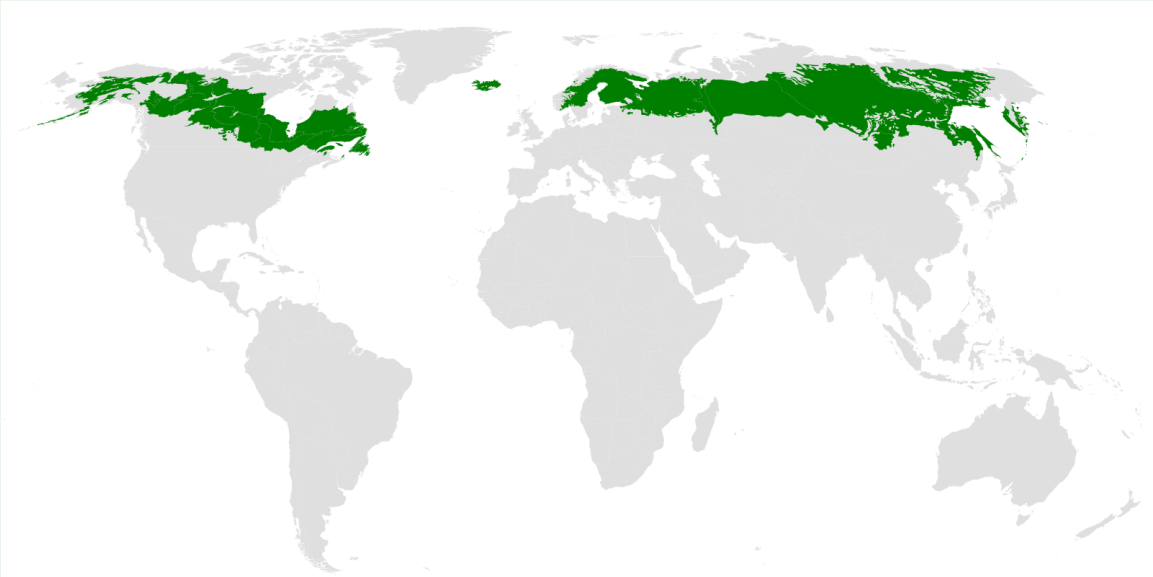

Figure $8.a$ World map with shading indicating the location of the taiga biome. Image by Mark Baldwin-Smith (licensed under CC-BY-SA 4.0)

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8.1: Climate and Biomes

8.2: Terrestrial Biomes

8.3: Aquatic Biomes

8.4: Data Dive- Biome Carbon Storage

8.5: Review

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8.1: Climate and Biomes

Biomes are large-scale environments that are distinguished by characteristic climate and vegetation (figure $8.1.a$). Biomes are also characterized by the animals and other organisms there, which are influenced by vegetation and climate patterns. 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. Altitude and latitude, which affect temperature and precipitation determine the distribution of biomes.

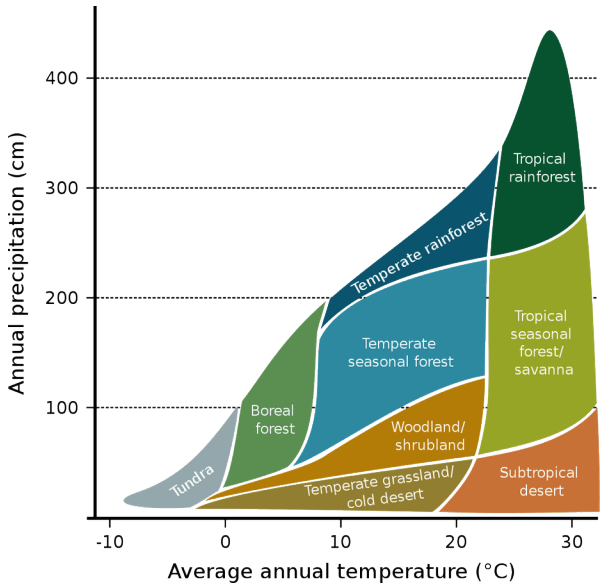

Figure $8.1.a$: Average annual temperature and annual precipitation are two climatic factors that determine the distribution of biomes. This graph shows annual precipitation in centimeters on the y-axis and average annual temperature in degrees Celsius on the x-axis. Tropical rainforests have the highest temperatures and most precipitation. Tropical seasonal forests and savannas have high temperatures (20-30°C) with precipitation from approximately 50 to 270 centimeters. Subtropical deserts have similarly high temperatures but dry conditions. Temperate grasslands and cold deserts range in average annual temperature from below 0 to 22°C and have less than 50 centimeters of precipitation per year. Woodlands/shrublands (such as the chaparral) have the same temperature range as cold deserts but can receive a little over 100 cm of precipitation per year. Temperate forests have intermediate temperatures (approximately 16-22°C), but temperate rainforests receive more precipitation than temperate seasonal forests. Boreal forests receive a little less precipitation than temperate forests, but are colder (approximately 1-10°C). The tundra has the coldest temperatures and little precipitation. Deserts have a range of temperatures but low precipitation. Image by Navarras (public domain).

Low latitudes (near the equator) have high temperatures, while high latitudes (near the poles) have low temperatures. This is because the sun hits the equator more directly. Sunlight hits the poles at an angle, reducing the intensity of light (and heat energy) per unit of area. Temperature also decreases with altitude. At high altitudes, the atmosphere is thinner and traps less heat energy from the sun. Because temperatures decline with altitude as well as latitude, similar biomes exist on mountains even when they are at low latitudes. As a rule of thumb, a climb of 1000 feet (about 300 m) is equivalent in changed flora and fauna to a trip northward of some 600 miles (966 km).

Where precipitation is moderately abundant — 40 inches (about 1 m) or more per year — and distributed fairly evenly throughout the year, the major determinant is temperature. It is not simply a matter of average temperature, but includes such limiting factors as whether it ever freezes or length of the growing season. Biomes are thus characterized not only by average temperature and precipitation but also their seasonality.

Not only does latitude influence temperature, but it also affects precipitation. For example, deserts tend to occur at latitudes of around 30° and at the poles, both north and south, driven by circulation and prevailing wind patterns in the atmosphere. The engine that drives circulation in the atmosphere and oceans is solar energy, which is determined by the average position of the sun over the Earth's surface. Direct light provides uneven heating depending on latitude and angle of incidence, with high solar energy in the tropics, and little or no energy at the poles. Atmospheric circulation and geographic location are the primary causal agents of deserts. At approximately 30° north and south of the equator, sinking air produces **trade wind deserts** like the Sahara and the Outback of Australia (figure $8.1.b$).

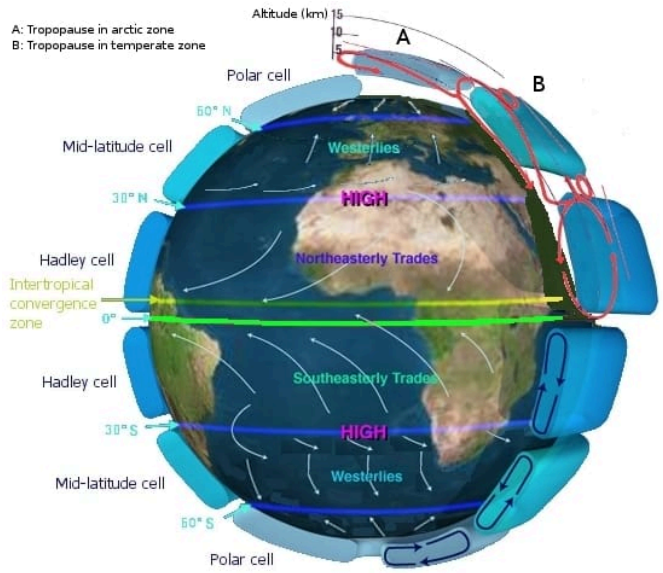

Figure $8.1.b$: The generalized circulation of the atmosphere. Solar energy falling on the equatorial belt heats the air and causes it to rise. The rising air cools and its contained moisture falls back on the tropics as rain. The drier air then continues to spread toward the north and south where it sinks back at about 30 degrees north and south latitudes. This sinking drier air creates belts of predominant high pressure along which desert conditions prevail. These belts of predominantly high pressure have air that descends along these belts and flows either north to become the westerlies or south to become the trade winds. Note the arrows indicating general directions of winds in the latitude zones. The trade winds are predominant in the tropics and the westerlies in the mid-latitudes.

The MinuteEarth video below discusses the global climate patterns which lead to deserts.

YouTube Video

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

View this YouTube Video online

Rainshadow deserts are produced where prevailing winds with moist air dries as it is forced to rise over mountains. The prevailing winds in the western half of North America blow in from the Pacific laden with moisture. Each time this air rises up from the western slopes of, successively, the Coast Ranges, the Sierras and Cascades, and finally the Rockies, it cools and its capacity to hold moisture decreases. The excess moisture condenses to rain or snow, which drenches the mountain slopes beneath. When the air reaches the eastern slopes, it is relatively dry, and much less precipitation falls. This phenomenon is called the **rainshadow effect** (figure $8.1.c$). How much rain falls and when influences the type of biome. For example, the **Great Basin Desert** (figure $8.1.d$) is a rain shadow desert produced as moist air from the Pacific rises by lifting over the Sierra Nevada Mountain (and other) and loses moisture from previous condensation and precipitation on the rainy side of the range(s).

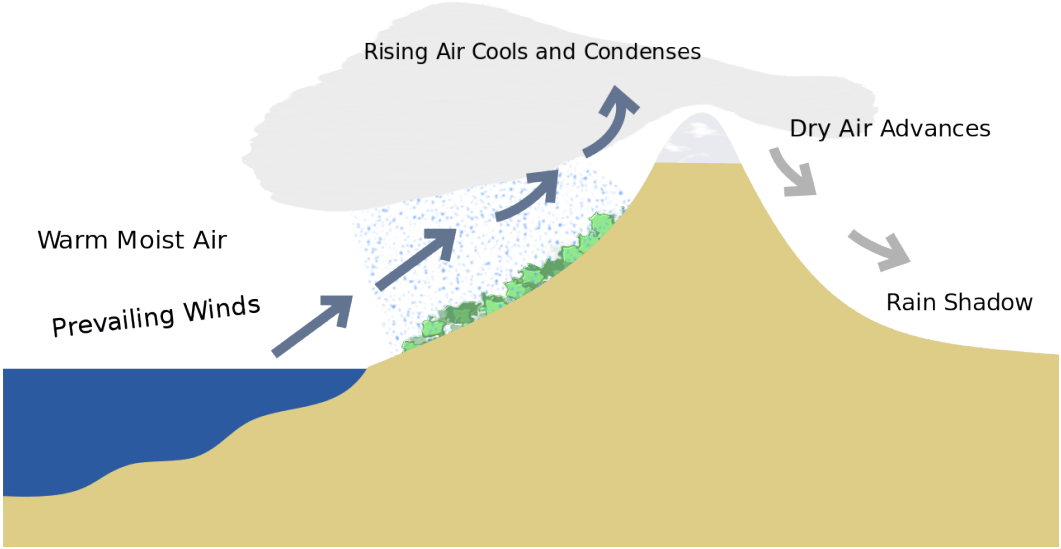

Figure 8.1.c: The rain shadow effect. Warm, moist air is carried up a mountain by prevailing winds. The rising air cools and condenses, resulting in precipitation as it moves up the mountain. The dry air advances down the other side of the mountain, resulting in a rain shadow (a dry region). Image by domdomegg (CC-BY).

Figure 8.1.d: Map of the Great Basin Desert. Image by USGS (public domain).

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8.2: Terrestrial Biomes

Because each biome is defined by climate, the same biome can occur in geographically distinct areas with similar climates (figure $8.2.a$). You can further explore the distribution of biomes using the HHMI Biome Viewer.

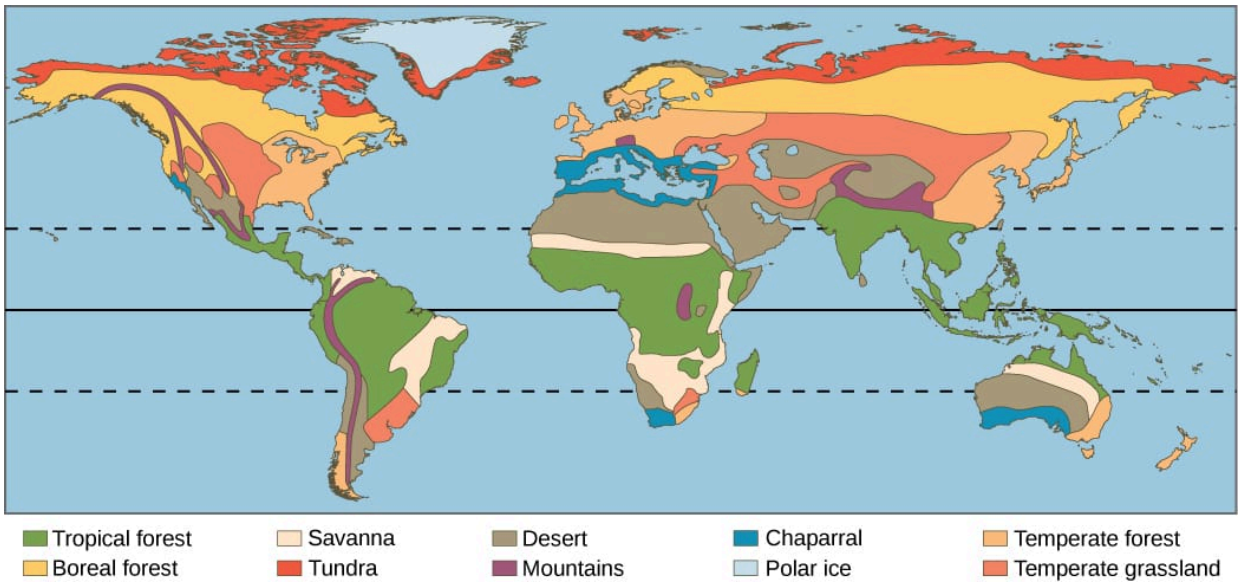

Figure $8.2.a$: Each of the world's eight major biomes is distinguished by characteristic temperatures and amount of precipitation. Tropical forests are found closest to the equator (solid black line). Savannas are just north or south of tropical forests. Deserts occur at 30 degrees north and south (dashed black line). Chaparral is in southern California, around the Mediterranean sea, at the southern tip of Africa, and along the southwestern Australian coast. Temperate forests are found the eastern United States, tip of South America, western Europe, northeastern Asia, eastern Australia, and New Zealand. Boreal forests are found in Canada, Scandinavian countries, and Russia. Temperate grasslands are found in western South America, the central United States, western Europe, and central Asia. Tundra is at the north of the map. Much of Greenland is polar ice. Key mountains include the Sierra Nevada, Rocky Mountains, Andes, and Mitumba Mountains.

There are eight major terrestrial biomes: tropical rainforests, savannas, deserts, chaparral, temperate grasslands, temperate forests, taiga (boreal forests), and Arctic tundra.

Tropical Rainforests

Tropical rainforests, found in equatorial regions (figure $8.2.a$), are the most biodiverse terrestrial biome (figure $8.2.b$). In the Western Hemisphere, the tropical rain forest reaches its fullest development in the jungles of Central and South America. The trees are very tall and of a great variety of species. One rarely finds two trees of the same species growing close to one another. Most of the animals — mammals and reptiles, as well as birds and insects — live in the trees.

Figure $8.2.b$: 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)

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. The broad-leafed trees are mostly **evergreen**, with leaves that persist throughout the year, but in tropical seasonal forests (see below), some are **deciduous,** with leaves falling off in the dry 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 **net primary productivity** (a measure of how carbon is stored by the photosynthesis that occurs in a community).

The annual rainfall in tropical rainforests ranges from 125 to 660 cm (50–200 in). Some tropical rainforests have relatively consistent rainfall whereas others (the **tropical seasonal forests**) have distinct 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. Nevertheless, the driest month of a tropical rainforest can still exceed the annual rainfall of some other biomes, such as deserts.

Tropical rainforests are characterized by vertical layering of vegetation and the formation of distinct habitats for animals within each layer. The vegetation is so dense that little light reaches the forest floor. 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.

Epiphytes

Epiphytes are plants that live perched on sturdier plants. They do not take nourishment from their host as parasitic plants do. Because their roots do not reach the ground, they depend on the air to bring them moisture and inorganic nutrients. Examples of epiphytes include many orchids, ferns (figure $8.2.c$), and bromeliads (members of the pineapple family like "Spanish moss").

Figure $8.2.c$: Epiphytes, graceful fern (*Niphidium crassifolium*), grow at the Soberania National Park in Panama. Image by Katja Schulz (CC-BY)

Tropical Soils

While productivity is high in tropical rainforests, the soils themselves tend to be of very poor quality. Because of the high rainfall, nutrients are quickly washed out of the topsoil unless they are incorporated in the forest plants. As plant and animal debris falls to the ground, it is quickly decomposed because of the warmth and moisture there. Thus minerals are found mainly in the forest plants, not in the soil. When the plants are removed and cultivation attempted, the soils quickly lose fertility. The situation is made worse by the lack of humus. Additionally, the topsoil may be no thicker than 5 cm (~2 inches), and most of these soils have high iron and aluminum content. Once exposed to the sun, these soils quickly bake into a bricklike material that cannot be cultivated.

Savannas

Savannas have mostly **perennial, herbaceous** plants (non-woody plants that persist for more than one year) with scattered trees, and they are located in Africa, South America, and northern Australia. Savannas are usually hot, tropical areas with temperatures averaging from 24 °C to 29 °C (75 °F to 84 °F) and an annual rainfall of 10–40 cm (3.9–15.7 in). Savannas have an extensive dry season; for this reason, forest trees do not grow as well as they do in the tropical rainforest. As a result, grasses and **forbs** (herbaceous plants other than grasses) are dominant (figure $8.2.d - e$). Since fire is an important source of disturbance in this biome, plants have evolved well-developed root systems that allow them to quickly resprout after a fire. Depending on the region, large grazing animals like giraffes, zebras, and gazelles and their predators (cheetahs, lions, etc.) are found in savannas.

Figure 8.2.d: Savannas, like this one in Taita Hills Wildlife Sanctuary in Kenya, are dominated by grasses. (credit: Christopher T. Cooper)

Figure 8.2.e: 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)

Deserts

Deserts exist between 15° and 30° north and south latitude. As discussed in the previous section (Climate and Biomes), deserts are frequently located on the downwind, or lee side, of mountain ranges due to the rain shadow effect. This is typical of the North American deserts, such as the Mohave and Sonoran deserts and the previously mentioned Great Basin Desert. Deserts in other regions (tradewind deserts), such as the Sahara and the Outback of Australia (both previously mentioned) as well as the Namib Desert in southwestern Africa and are dry because of the high-pressure, dry air descending at those latitudes.

Deserts are very dry; evaporation typically exceeds precipitation. 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 deserts located in central Australia ("the Outback") and northern Africa.

Hot deserts (subtropical deserts) can have daytime soil surface temperatures above 60°C (140°F) and nighttime temperatures approaching 0°C (32°F). **Cold deserts** that experience freezing temperatures during the winter and any precipitation is in the

form of snowfall. The largest of these deserts are the Gobi Desert in northern China and southern Mongolia, the Taklimakan Desert in western China, the Turkestan Desert, and the Great Basin Desert of the United States.

The 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 $8.2.f$). Seed plants in the desert produce seeds that can lie dormant for extended periods between rains. Most animal life in deserts has adapted to a nocturnal life, spending the hot daytime hours beneath the ground. The Namib Desert is the oldest on the planet, and has probably been dry for more than 55 million years. It supports a number of endemic species (species found only there) because of this great age. For example, the unusual gymnosperm *Welwitschia mirabilis*is the only extant species of an entire order of plants. There are also five species of reptiles considered endemic to the Namib.

Figure $8.2.f$: 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)

Many of the animals in the desert (mammals, lizards and snakes, insects, and even some birds) are adapted for burrowing to escape the scorching heat of the desert sun. Many of them limit their forays for food to the night.

The net primary productivity of the desert is low. High productivity can sometimes be achieved with **irrigation**, but these gains are often only temporary because it leads to the buildup of **salts** and **minerals**. Large areas of formerly unproductive desert in the United States, Israel, and Egypt have been converted into fertile fields through irrigation. However, even the best irrigation water contains dissolved salts. Because the rainfall in deserts is so low, any water that does not immediately run off remains near the surface and is largely lost by evaporation. The salts it carries are left near the top of the soil. Their accumulation may make the soil so alkaline (basic) and so salty that it is prohibitive to agriculture (figure $8.2.g$). In the U. S., the situation is especially severe in the Great Basin because water flowing down from the mountains—bearing its load of dissolved salts—cannot flow on to the ocean but simply flows out onto the valley floors and evaporates.

Figure $8.2.g$: Salt formations at the Badwater Basin in Death Valley, California. Minerals accumulate when water pools in this low-lying area, making conditions impossible for agriculture. Some plants, like pickleweed and saltgrass, are adapted to grow around the edges of the salt flats. Image by "Mike" Michael L. Baird (CC-BY).

Mediterranean Scrub (Chaparral)

The **Mediterranean scrub**, is also called chaparral or scrub forest and is found in California, along the Mediterranean Sea, and along the southern coast of Australia (figure $8.2.h$). 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.

Figure $8.2.h$: The chaparral is dominated by shrubs. (credit: Miguel Vieira)

The Mediterranean scrub 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. The trees in the chaparral are mostly oaks, both deciduous and evergreen. Scrub oaks and shrubs like manzanita and the California lilac (not a relative of the eastern lilac) form dense, evergreen thickets. All of these plants are adapted to drought by such mechanisms as waxy, waterproof coatings on their leaves. Many plants that thrive in one chaparral region are successfully cultivated in other chaparral regions. For example, vineyards, olives, and figs from their native Mediterranean and eucalyptus trees from Australia thrive in California. However, blue gum eucalyptus from Australia disrupts California ecosystems by changing the hydrology and outcompeting native plants.

Temperate Grasslands

Temperate grasslands are found throughout central North America, where they are also known as prairies (figure $8.2.i$), and in Eurasia, where they are known as steppes. Temperate grasslands have pronounced annual fluctuations in temperature with hot summers and cold winters. The annual temperature variation produces specific growing seasons for plants. Plant growth is possible when temperatures are warm enough to sustain plant growth, which occurs in the spring, summer, and fall.

Figure $8.2.h$: 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)

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. 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.

Annual precipitation ranges from 25.4 cm to 88.9 cm (10–35 in) and is concentrated in the summer and spring. In the plains of North America, the annual rainfall is sufficiently low (~50 cm, 20") that little or no rainfall percolates down to the water table. Calcium and other minerals are not carried below the reach of plant roots and so remain available for use. This keeps the pH and general fertility high. The grasses in undisturbed prairie are perennial. Their extensive root systems help prevent soil erosion, and the return of the season's above-ground growth to the topsoil returns minerals and provides humus to it. These advantages are diminished when annual grasses such as wheat and corn are grown instead and removed in the harvest.The self-restoring fertility of the soils of the plains states accounts for this region being the "breadbasket" of the nation (and other countries as well).

Temperate Forests

Temperate forests are the most common biome in eastern North America, Western Europe, Eastern Asia, Chile, and New Zealand (figure $8.2.i$). 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.

Figure $8.2.i$: Deciduous trees are the dominant plant in the temperate forest. (credit: Oliver Herold)

Temperate forests may be deciduous, mixed (with deciduous and evergreen trees), or coniferous (with evergreen conifers). Examples of temperate deciduous trees are beech, maple, oak, and hickory. The deciduous trees of temperate forests drop their leaves in the winter; thus, little photosynthesis occurs during the dormant winter period. (In other biomes, such as chaparral and tropical seasonal forests, trees or shrubs may drop their leaves during the summer or dry season.) 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. Large stands dominated by a single species are common.

The deciduous 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. Deer, raccoons, and salamanders are characteristic inhabitants of temperate forests.

Precipitation is relatively constant throughout the year and ranges between 75 cm and 150 cm (29.5–59 in). Enough water falls on the soil so that much of it soaks deep into the ground and carries minerals with it. Such soils tend to be acidic and of low and (if unattended) diminishing fertility. Only by regular fertilization and liming (to restore calcium and raise pH) can productive agriculture be carried out in them. In the U.S., the soils east of the Appalachian Mountains tend to be of this sort.

Taiga

The **taiga**, also known as **boreal forest** in North America, is found roughly between 50° and 60° north latitude across most of Canada, Alaska, Russia, and northern Europe ((figure $8.2.i$). 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. Although precipitation is relatively low, the taiga is dotted with lakes, bogs, and marshes because the cold temperatures limit evaporation.

Figure $8.2.j$: The boreal forest (taiga) has low lying plants and conifer trees. (credit: L.B. Brubaker, NOAA)

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. In the taiga, evergreen trees grow faster than deciduous trees. 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.

In North America, the moose is such a typical member that it has led to the name: "spruce-moose" biome. Deer, bears, and wolves are also found in the taiga. Before the long, snowy winter sets in, many of the mammals hibernate, and many of the birds migrate south.

The net primary productivity of taiga is lower than that of temperate forests and tropical rainforests. The aboveground **biomass** (mass of living organisms) of taiga 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. Taiga lacks the layered forest structure seen in tropical rainforests or, to a lesser degree, temperate forests. The structure of the taiga is often only a layer of trees and the understory of low-lying plants and lichen. When conifer needles are dropped, they decompose more slowly than broad leaves; therefore, fewer nutrients are returned to the soil to fuel plant growth.

At the coldest parts of the taiga, the soil remains frozen year after year, forming a layer called **permafrost**. When the permafrost melts in unusually warm years, the trees are no longer supported by this hard surface and lean in different directions, forming a "drunken forest". At extreme latitudes, the trees of the taiga become stunted by the harshness of the subarctic climate. Where they finally disappear (above the "tree line"), the Arctic tundra begins.

Arctic Tundra

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 taiga, there is little evaporation because of the cold temperatures.

There is little species diversity, low net primary productivity, and low above-ground biomass. Like some of the taiga, the soils of the Arctic tundra may remain in a perennially frozen state, forming 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 surface layer of soil above the permafrost melts in the brief summer, water is released and provides for a burst of productivity

while temperatures and long days permit it. Because of these harsh growing conditions, the Arctic tundra is particularly sensitive to disturbances (disruptions that decrease biomass, such as heavy machinery passing through and squishing some of the plants).

Plants in the Arctic tundra are generally low to the ground and include low shrubs, sphagnum moss, grasses, lichens, and small flowering plants (figure $8.2.k$). Caribou feed on this growth as do vast numbers of insects. Swarms of migrating birds, especially waterfowl, invade the tundra in the summer to raise their young, feeding them on a large variety of aquatic invertebrates and vertebrates. As the brief arctic summer draws to a close, the birds fly south, and all but a few of the permanent residents, in one way or another, prepare themselves to spend the winter in a dormant state.

Figure $8.2.k$: Low-growing plants such lichen and grasses are common in tundra. Credit: Nunavut tundra by Flickr: My Nunavut is licensed under CC-BY.

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8.3: Aquatic Biomes

Abiotic Factors Influencing Aquatic Biomes

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

Marine Biomes

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

Ocean

The physical diversity of the ocean is a significant influence on plants, animals, and other organisms. The ocean is categorized by several areas (Figure $8.3.a$). Each area has a distinct group of species adapted to the biotic and abiotic conditions particular to it. The **intertidal zone**, which is the zone between high and low tide, is the oceanic region that is closest to land. Generally, most people think of this portion of the ocean as a sandy beach. In some cases, the intertidal zone is indeed a sandy beach, but it can also be rocky or muddy. Organisms are exposed to air and sunlight at low tide and are underwater most of the time, especially during high tide. Therefore, living things that thrive in the intertidal zone are adapted to being dry for long periods of time. The shore of the intertidal zone is also repeatedly struck by waves, and the organisms found there are adapted to withstand damage from the pounding action of the waves (figure $8.3.b$). The exoskeletons of shoreline crustaceans (such as the shore crab, *Carcinus maenas*) are tough and protect them from desiccation (drying out) and wave damage. Another consequence of the pounding waves is that few algae and plants establish themselves in the constantly moving rocks, sand, or mud.

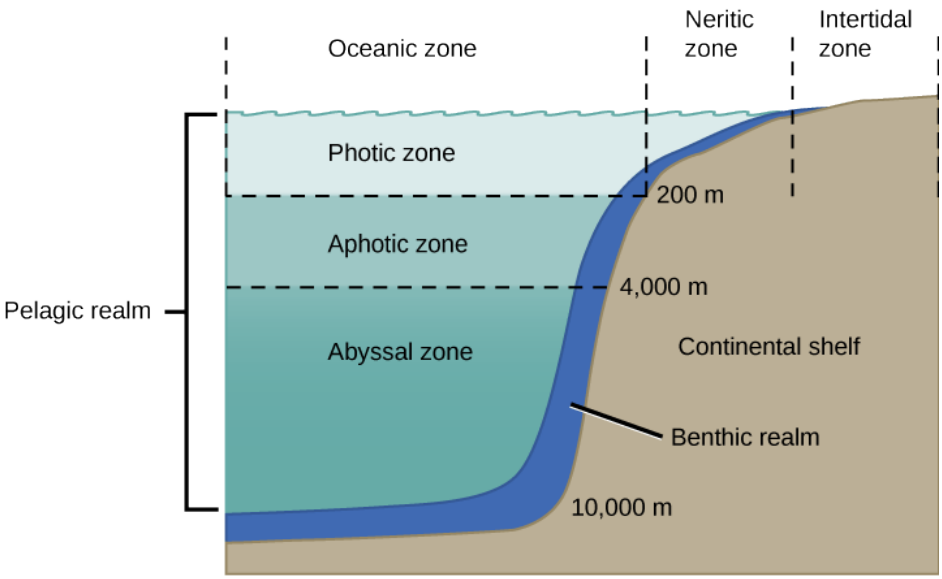

Figure 8.3.a: The ocean is divided into different zones based on distance from the shoreline and water depth. The intertidal zone is the closest to shore followed by the neretic and oceanic zone. The photic zone is 0-200 meters deep. The aphotic zone is 200-4,000 meters deep. The abyssal zone is 4,000-10,000 meters deep. These three zones form the pelagic realm, and the benthic realm is below the pelagic realm, along the continental shelf.

Figure 8.3.b: Sea urchins, mussel shells, and starfish are often found in the intertidal zone, shown here in Kachemak Bay, Alaska. (credit: NOAA)

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

Beyond the neritic zone is the open ocean area known as the **oceanic zone**. Within the oceanic zone there is thermal stratification where warm and cold waters mix because of ocean currents. Abundant plankton serve as the base of the food chain for larger animals such as whales and dolphins. Nutrients are scarce and this is a relatively less productive part of the marine biome. When photosynthetic organisms and the protists and animals that feed on them die, their bodies fall to the bottom of the ocean where they remain.

All of the ocean's open water is referred to as the **pelagic realm**. The pelagic realm is divided into the photic, aphotic, and abyssal zones from top to bottom based on how far light reaches into the water. The **photic zone**, which is the portion of the ocean that light can penetrate (approximately 200 m or 650 ft). At depths greater than 200 m, light cannot penetrate; thus, this is referred

to as the **aphotic zone**. The majority of organisms in the aphotic zone include sea cucumbers (phylum Echinodermata) and other organisms that survive on the nutrients contained in the dead bodies of organisms in the photic zone.

The deepest part of the ocean is the **abyssal zone**, which is at depths of 4000 m or greater. Both the aphotic and abyssal zones lack sufficient light for photosynthesis, and together, they constitute most of the ocean. 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 deep. These zones are relevant to freshwater lakes as well. The abyssal zone is very cold and has very high pressure, high oxygen content, and low nutrient content. There are a variety of invertebrates and fishes found in this zone, but the abyssal zone does not have plants because of the lack of light. Cracks in the Earth's crust called **hydrothermal vents** are found primarily in the abyssal zone (figure $8.3.c$). Around these vents, bacteria that utilize the hydrogen sulfide and other minerals emitted as an energy source serve as the base of the food chain found in the abyssal zone.

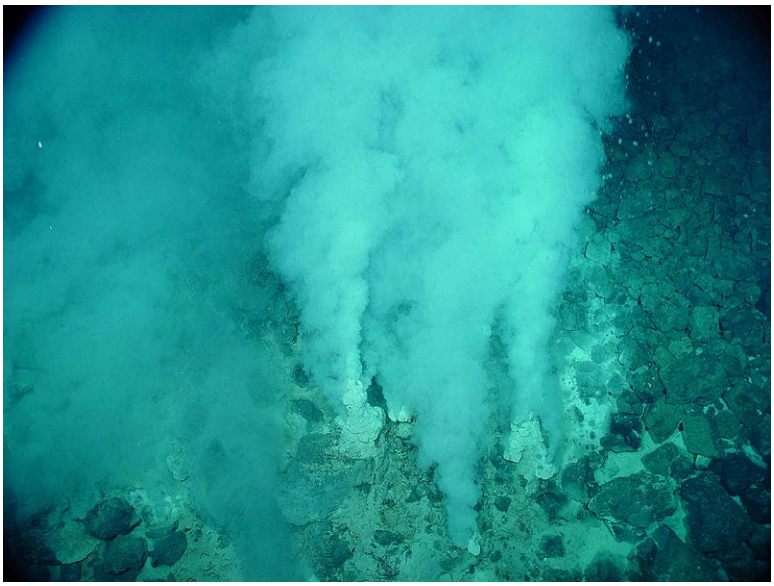

Figure $8.3.c$: A hydrothermal vent. Image by NOAA (public domain).

The **benthic realm**, extends along the ocean bottom from the shoreline to the deepest parts of the ocean floor. It is comprised of sand, silt, and dead organisms. This is a nutrient-rich portion of the ocean because of the dead organisms that fall from the upper layers of the ocean. Because of this high level of nutrients, a diversity of sponges, sea anemones, marine worms, sea stars, fishes, and bacteria exist.

Coral Reefs

Coral reefs are characterized by high biodiversity and the structures created by invertebrates that live in warm, shallow waters within the photic zone of the ocean. They are mostly found within 30 degrees north and south of the equator. The Great Barrier Reef is a well-known reef system located several miles off the northeastern coast of Australia. The coral organisms are colonies of saltwater polyps that secrete a calcium carbonate skeleton. These calcium-rich skeletons slowly accumulate, forming the underwater reef (figure $8.3.d$).

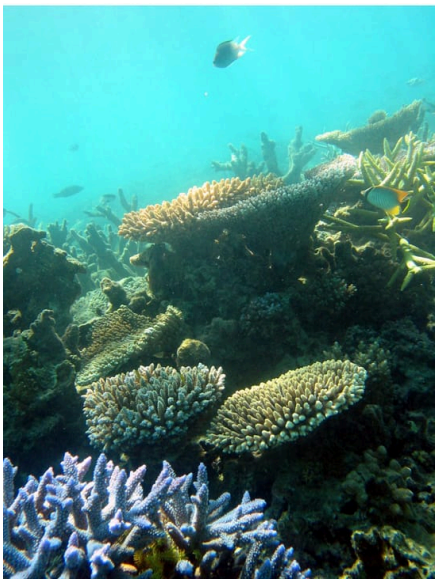

Figure 8.3.d: Coral reefs are formed by the calcium carbonate skeletons of coral organisms, which are marine invertebrates. (credit: Terry Hughes)

Corals found in shallower waters (at a depth of approximately 60 m or about 200 ft) have a mutualistic relationship with photosynthetic unicellular algae called dinoflagellates. 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. Some corals living in deeper and colder water do not have a mutualistic relationship with algae; these corals attain energy and nutrients using stinging cells on their tentacles to capture prey. It is estimated that more than 4,000 fish species inhabit coral reefs. These fishes can feed on coral, other invertebrates, or the seaweed and algae that are associated with the coral.

Estuaries: Where the Ocean Meets Fresh Water

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

The short-term and rapid variation in salinity due to the mixing of fresh water and salt water is a difficult physiological challenge for the plants and animals that inhabit estuaries. Many estuarine plant species are **halophytes**, plants that can tolerate salty conditions. Halophytic plants are adapted to deal with the salinity resulting from saltwater on their roots or from sea spray. In some halophytes, filters in the roots remove the salt from the water that the plant absorbs. Other plants are able to pump oxygen into their roots. Animals, such as mussels and clams, 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 stop using 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 using oxygen.

Freshwater Biomes

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

Lakes and Ponds

Lakes and ponds can range in area from a few square meters to thousands of square kilometers. Temperature is an important abiotic factor affecting living things found in lakes and ponds. In the summer, thermal stratification of lakes and ponds occurs when the upper layer of water is warmed by the sun and does not mix with deeper, cooler water. Like oceans, lakes and ponds have photoic zones through which light can penetrate and aphotic zones without light. **Phytoplankton** (small photosynthetic organisms such as algae and photosynthetic bacteria that float in the water) are found here and carry out photosynthesis, providing the base of the food web of lakes and ponds. **Zooplankton** (very small animals that float in the water), such as rotifers and small crustaceans, consume these phytoplankton (figure $8.3.e$). At the bottom of lakes and ponds, bacteria in the aphotic zone break down dead organisms that sink to the bottom.

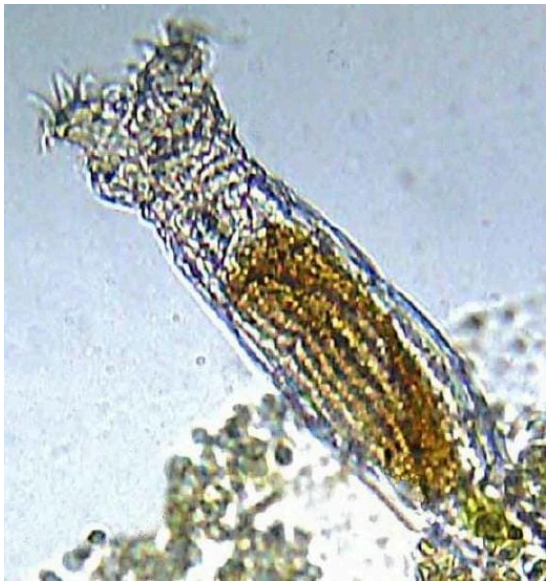

Figure $8.3.e$: A rotifer is an example of the zooplankton found in lakes and ponds. Image by Bob Blaylock at English Wikipedia (CC-BY-SA).

Rivers and Streams

Rivers and streams are continuously moving bodies of water that carry large amounts of water from the source, or headwater, to a lake or ocean. The largest rivers include the Nile River in Africa, the Amazon River in South America (Figure $8.3.f$), and the Mississippi River in North America. Abiotic features of rivers and streams vary along the length of the river or stream. Streams begin at a point of origin referred to as source water. The source water is usually cold, low in nutrients, and clear. The channel (the width of the river or stream) is narrower than at any other place along the length of the river or stream. Because of this, the current is often faster here than at any other point of the river or stream.

Figure $8.3.f$: The Amazon River is the world's largest river. Image by Jason Hollinger (CC-BY)

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

As the river or stream flows away from the source, the width of the channel gradually widens and the current slows. This slow-moving water, caused by the gradient decrease and the volume increase as tributaries unite, has more sedimentation. Phytoplankton can also be suspended in slow-moving water. Therefore, the water will not be as clear as it is near the source. The water is also warmer. Worms and insects can be found burrowing into the mud. The higher order predator vertebrates include waterfowl, frogs, and fishes.

Wetlands

Wetlands are environments in which the soil is either permanently or periodically saturated with water. Wetlands are different from lakes because wetlands are shallow bodies of water that may periodically dry out. Emergent vegetation consists of wetland plants that are rooted in the soil but have portions of leaves, stems, and flowers extending above the water's surface. There are several types of wetlands including marshes, swamps, bogs, mudflats, and salt marshes (figure $8.3.g$).

Figure $8.3.g$: Located in southern Florida, Everglades National Park is vast array of wetland environments, including sawgrass marshes, cypress swamps, and estuarine mangrove forests. Here, a Great Egret walks among cypress trees. (credit: NPS)

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8.4: Data Dive- Biome Carbon Storage

Overview

Carbon sequestration is the process by which atmospheric carbon dioxide is taken up by trees, grasses, and other plants through photosynthesis and stored as carbon in biomass (trunks, branches, foliage, and roots). Carbon storage can also occur in soil formed from organic matter found in decomposing litter. Terrestrial carbon sequestration has been a recent topic of interest because of its implications for use in climate change mitigation. The carbon storage in terrestrial biomes helps to offset sources of carbon dioxide to the atmosphere, such as deforestation, wildfires, and fossil fuel emissions. As such, carbon storage in each biome can be altered by both natural and human caused events. The figure below indicates the estimated storage above (plants) and below (soil) ground by terrestrial biomes:

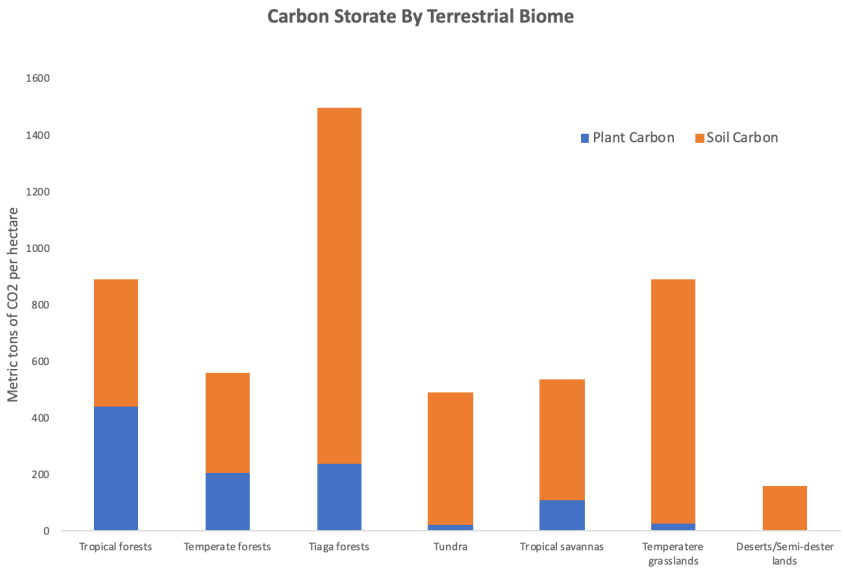

Figure $8.4.a$: Carbon storage (in metric tons of CO2 per hectare) above (plant) and below (soil) ground in various biomes. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Islam KK, Sato N 2012.

Questions

1. What kind of graph is this?
2. What is the independent (explanatory) variable and the dependent (response) variable?
3. Which biome has the greatest storage in plants? What about soil?
4. What are the top three terrestrial biomes in terms of their carbon storage?
5. How can the results of this graph to inform future conservation efforts?
6. What do the results of this graph make you curious about?

Raw Data From Above Graph(s)

Table $8.4.a$**:** Raw data of carbon storage (in metric tons of CO2 per hectare) above (plant) and below (soil) ground in various biomes. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Islam KK, Sato N 2012.

Biome	Plant Carbon	Soil Carbon	Total Carbon
Tropical Forests	442	450	892
Temperate Forests	208	352	561

Biome	Plant Carbon	Soil Carbon	Total Carbon
Taiga Forests	236	1260	1496
Tundra	23	467	490
Tropical Savannas	108	430	538
Temperate Grasslands	26	865	892
Deserts/Semi-Desert Lands	6	154	160

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8.5: Review

Summary

After completing this chapter you should be able to...

- Describe how latitude and altitude affect temperature and precipitation, which in turn, determine the distribution of biomes.
- Compare the eight major terrestrial biomes.
- Describe how light, temperature, flow, and salinity influence aquatic biomes.
- Distinguish between marine and freshwater biomes and describe examples of each.
- Explain the different realms and zones of the ocean.

Earth has **terrestrial biomes** and **aquatic biomes**. Temperature and precipitation, and variations in both, are key abiotic factors that shape the composition of animal and plant communities in terrestrial biomes. There are eight major terrestrial biomes: **tropical rainforests, savannas, deserts, chaparral, temperate grasslands, temperate forests, taiga,** and **Arctic tundra**.

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. Aquatic biomes include both **marine biomes** and **freshwater biomes**. **Oceans**, **coral reefs**, and **estuaries** are marine biomes while **lakes**, **ponds**, **rivers**, **streams**, and **wetlands** are freshwater biomes.

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UNIT 3: CONSERVATION

Conservation biology is the management of Earth's ecosystems with the aim of protecting species, their communities, and ecosystems from escalated extinction rates and the destruction and degradation of their habitats. This field focuses on both evaluating past, current, and future trends and creating conservation action plans to reverse trends leading to extinction and destroyed habitats. More specifically, procedures have been put in place to protect threatened species, design habitat preserves, creating breeding programs, and reconciling conservation concerns with practical human needs.

As conservation biology needs to pull from so many fields, it is an interdisciplinary subject drawing on physical, life, and social sciences, as well as natural resource management procedures. The field seeks to integrate social science policy with theories from the fields of ecology, demography, taxonomy, and genetics. The principles underlying each of these disciplines have direct implications for the management of species and ecosystems, captive breeding and reintroduction, genetic analyses, and habitat restoration. Social science disciplines not only help with putting policies in place to legally protect species and habitats but also help fund conservation actions. Conservation action plans help direct research, monitoring, and education programs that engage concerns at both local and global scales.

The goal of this unit is to overview the essential conservation biology topics as we head into an uncertain future.

Figure $3.a$**:** A road heading into our uncertain future. Image by Pikist (Public domain)

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9: The Value of Biodiversity

9.1: Ecosystem Diversity

9.2: Species Diversity

9.3: Genetic Diversity

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10: Threats to Biodiversity

10.1: Extinction

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10.3: Habitat Loss

10.4: Overexploitation

10.5: Pollution

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10.7: Climate Change

10.8: Data Dive- Threats to Biodiversity

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11: Protecting Biodiveristy

11.1: Policies

11.2: Non-profit Organizations

11.3: Species-level Conservation

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11.6: Economic Influences on Conservation

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Thumbnail image - "Environmental protection" is in the Public Domain

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9: THE VALUE OF BIODIVERSITY

Chapter Hook

Most of the medicine we depend on today originated because of the diversity of plants across the globe. New medicines sometimes come from newly found species, but there is still much to learn from already discovered species as well. In 2019, research was published about a newly discovered quality on a well-known California plant called yerba santa (*Eriodictyon californicum*). Among native people of California, yerba santa was already well known to have medicinal qualities, but only recently did research scientists begin to test them. It was discovered that a compound in yerba santa decreases the onset of Alzheimer's disease, a leading cause of death in the United States, by having protective and supportive qualities on the neurons in our nervous system. This research is not only vital from a medical perspective, but also exemplifies the importance of protecting diversity.

Figure $9.a$ Yerba santa (*Eriodictyon californicum*) in bloom. Image by Breck22 (Public domain)

Biodiversity is a broad term for the variety of life on Earth. Traditionally, ecologists have measured biodiversity by taking into account both the number of species and the number of individuals of each species. However, biologists now measure biodiversity at a number of organizational levels, including ecosystem, species, and genetic diversity. This focuses efforts to preserve the biologically and technologically important elements of biodiversity. 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.

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9.1: Ecosystem Diversity
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9.1: Ecosystem Diversity

Measuring biodiversity on a large scale involves measuring **ecosystem diversity**, the number of different ecosystems on Earth or in a geographical area as well as their relative abundances (figure $9.1.a$). The loss of an ecosystem means the loss of the interactions between species and the loss of biological productivity that an ecosystem is able to create. An example of a largely extinct ecosystem in North America is the prairie ecosystem (figure $9.1.a$). Prairies once spanned central North America from the boreal forest in northern Canada down into Mexico. They are now all but gone, replaced by crop fields, pasture lands, and suburban sprawl. Many of the species survive, but the hugely productive ecosystem that was responsible for creating our most productive agricultural soils is now gone. As a consequence, their soils are now being depleted unless they are maintained artificially at great expense.

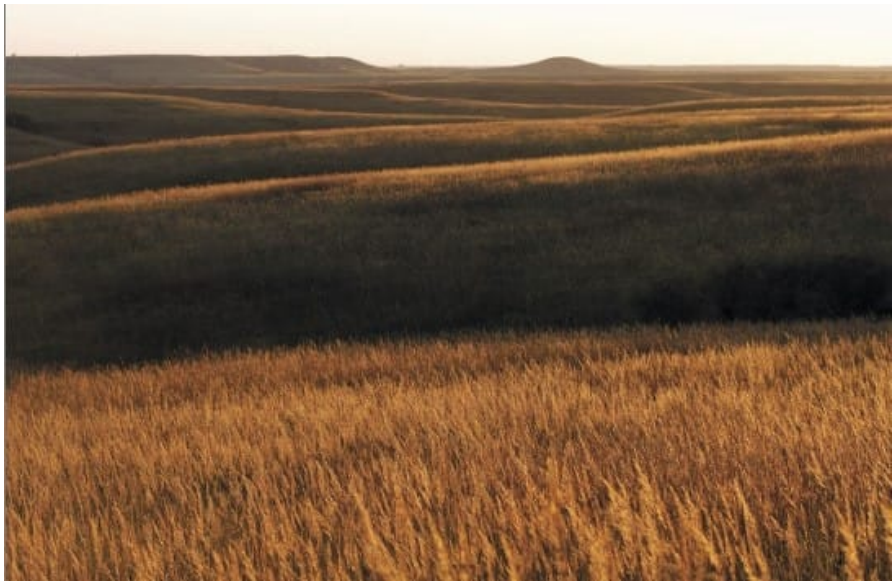

Figure $9.1.a$: The variety of ecosystems on Earth—from the coral reef (top) to prairie (bottom)—enables a great diversity of species to exist. Top image by Wise Hok Wai Lum (CC-BY-SA). Bottom image modified from Jim Minnerath, USFWS.

The soil productivity described above is an example of an **ecosystem service**. These are the products and processes associated with biological systems and are directly or indirectly of immense value to the well-being of people. Some ecosystem services are processes such as the regulation of climate, flooding, and disease. Nutrient cycling, pollination, and regulation of crop

pests are ecosystem services important to food production (see the Food Production and Ecosystem Services box below). The water cycle provides fresh water, and photosynthesis adds oxygen to our air. Other ecosystem services are human provisions including food, fuel, and fiber (such as cotton for clothing or timber). Medicines are another important provision (see Importance of Species Diversity). Furthermore, healthy ecosystems allow for recreational activities, such as hiking, kayaking, and camping, and educational opportunities, such as field trips. Nature is also the basis for a significant part of aesthetic and spiritual values held by many cultures.

In 1997, Robert Costanza and his colleagues estimated to annual value of ecosystem services to be $33 trillion dollars ($53 trillion in 2019 dollars), and many consider this to be an underestimation. For comparison the gross domestic product of the United States in 2020 was $21 trillion. Valuing ecosystem services can be difficult, particular for those services that are processes rather than provisions. One strategy is to calculate replacement cost. For example, how much would it cost to control a pest population if it was not regulated by natural processes? Figure $9.1.b$ illustrates the value of a few ecosystem services.

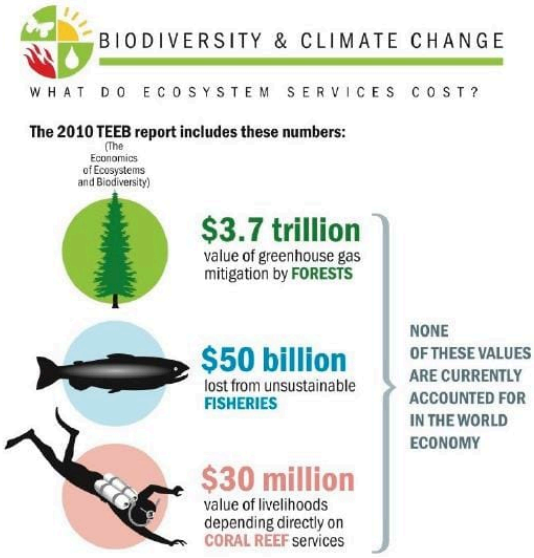

Figure $9.1.b$: The value of three ecosystem services. The question, "What do ecosystem services cost?" is partially answered by the 2010 TEEB (The Economics of Ecosystems and Biodiversity) report. Greenhouse gas mitigation (which limits climate change) provided by forests is valued at $3.7 trillion. Unsustainable fisheries have compromised fish availability, costing $50 billion. Coral reef services, such as tourism, are valued at $30 million. Values are in 2010 dollars. None of these values are currently accounted for in the world economy. Data from The Economics of Ecosystems and Biodiversity Synthesis Report. Image by Future Challenges (CC-BY-SA).

Food Production and Ecosystem Services

Food production relies on several interacting ecosystem services. Most soils 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** (farmable) soil is not practically possible. 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 phenomenon with complex and interacting causes.

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. A 2002 study by Claire Kremen and colleagues found that **native** pollinators in Central California (those that historically occurred there; figure $9.1.c$ and d) provided full pollination to watermelon crops. This was only true on organic farms that were located near the natural habitat for these pollinators, highlighting the importance of sustainable farming practices and habitat

conservation in preserving ecosystem services. Essentially, in a healthy ecosystem, native pollinators eliminated the need for rented honeybee hives. Note that while honeybees are valuable in an agricultural setting, they are not native to North America and can disrupt ecosystems by competing with native bees.

Figure $9.1.c$: The California bumble bee (*Bombus californicus*) is one of several native insects that provided watermelon pollination in Kremen and colleagues' study. Image by Rhododendrites (CC-BY-SA).

Figure $9.1.d$: Mason bees are efficient pollinators, and many are native to North America. Image by Robert Engelhardt (CC-BY-SA).

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 (see Industrial Agriculture and Environmental Toxicology). 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.

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Kremen, C., Williams, N. M., and Thorp, R. W. Crop pollination from native bees at risk from agricultural intensification. *PNAS* **99,** 6812-16816 (2002). DOI

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9.2: Species Diversity

Species diversity 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. 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. **Species richness**, the number of species living in a habitat or other unit, is one component of biodiversity. **Species evenness** is a component of species diversity based on **relative abundance** (the number individuals in a species relative to the total number of individuals in all species within a system). Foundation species (see Ecosystem Types and Dynamics) often have the highest relative abundance of species. Two locations with the same richness do not necessarily have the same species evenness. For example, both communities in figure $9.2.b$ have three different trees species and thus a species richness of three. However, there is a dominant species (represented by six individuals) in community #1. In community #2, there are three of individuals of each species. Therefore, community #2 has a greater species evenness and greater species diversity overall.

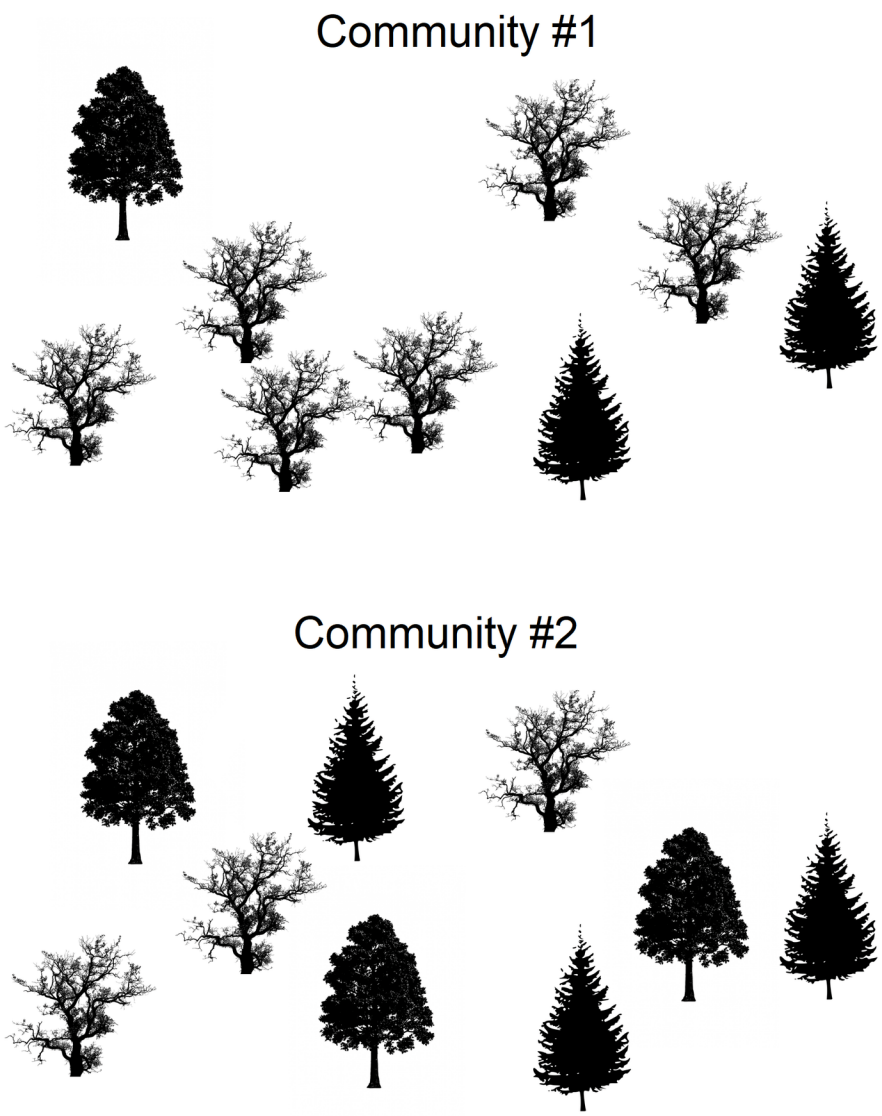

Figure $9.2.a$: Two hypothetical tree communities have the same species richness, but community #2 (bottom) has a greater species evenness. Both communities have nine trees and three tree species. In community #1, one species is dominant, represented by six individuals. There are two individuals of a conifer species, and only one individual of the final species. In community #2, there are three individuals from each species. Images compiled by Melissa Ha from Alone tree George Hodan, Old Tree Silhouette, and Tree (all public domain).

The Number of Species on Earth

Despite considerable effort, knowledge of the species that inhabit the planet is limited. About 1.5 million species have been described, but many more species are yet to be identified. Estimates of the total number of species on Earth range from 3 million to 100 million, with more recent estimates commonly ranging from 8 to 11 million species. A 2011 study suggests that only 13% of **eukaryotic** species (such as plants, animals, fungi, and algae) have been named (Table $9.2.a$. Estimates of numbers of **prokaryotic** species (such as bacteria) are largely guesses, but biologists agree that science has only just begun to catalog their diversity. In fact, a 2017 study by Brendan Larsen and colleagues estimated that there are actually 1-6 billion species on Earth with at least 70% of them being bacteria. Given that Earth is losing species at an accelerating pace, science knows little about what is being lost.

Table $9.2.a$***:*** *The estimated number of species by taxonomic group—including both described (named and studied) and predicted (yet to be named) species.*

Type of Organism	Mora et al. 2011 Described	Mora et al. 2011 Predicted	Chapman 2009 Described	Chapman 2009 Predicted	Groombridge and Jenkins 2002 Described	Groombridge and Jenkins 2002 Predicted
Animals	1,124,516	9,920,000	1,424,153	6,836,330	1,225,500	10,820,000
Photosynthetic protists (such as algae)	17,892	34,900	25,044	200,500	No data	No data
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	No data	No data	10,307	1,000,000	10,175	No data
Total	1,438,769	10,960,000	1,897,502	10,897,630	1,657,675	13,240,000

There are various initiatives to catalog described species in accessible and more organized ways, and the internet is facilitating that effort. Nevertheless, at the current rate of species description, which according to the State of Observed Species 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.

DNA Barcoding

The technology of molecular genetics and data processing and storage are maturing to the point where cataloging the planet's species in an accessible way is close to feasible. **DNA barcoding** is one molecular genetic method, which takes advantage of a specialized structures inside of some cells called mitochondria (figure $9.2.a$). **Mitochondria** contain DNA that is separate from the rest of the cell, and one of the genes in mitochondrial DNA changes more quickly through the process of evolution than regular DNA. While plants contain mitochondria, DNA from their **chloroplasts**, the specialized structures in which photosynthesis occurs, are more often barcoded. Rapid DNA sequencing technology make the molecular genetics portion of the work relatively inexpensive and quick. Computer resources store and make available the large volumes of data. Projects are currently underway to use DNA barcoding to catalog museum specimens, which have already been named and studied, as well as testing the method on less studied groups. As of mid 2012, close to 150,000 named species had been barcoded. Early studies suggest there are significant numbers of undescribed species that looked too much like sibling species to previously be recognized as different. These now can be identified with DNA barcoding.

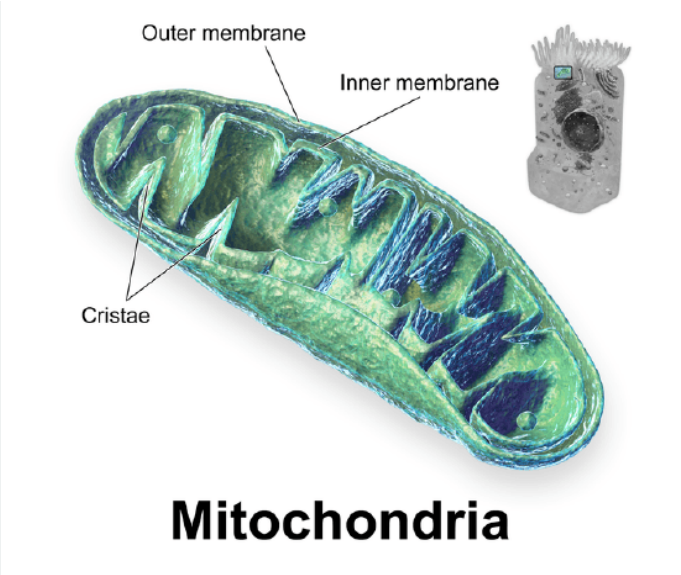

Figure $9.2.b$: Mitochondria are specialized structures inside of eukaryotic cells. They contain separate DNA, and mitochondrial DNA contains a rapidly evolving gene used for DNA barcoding. Image by Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". *WikiJournal of Medicine* **1** (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436. (CC-BY)

Importance of Species Diversity

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

Modern pharmaceutical science also recognizes the importance of these plant compounds. Examples of significant medicines derived from plant compounds include aspirin, codeine, digoxin, atropine, and vincristine (figure $9.2.c$). 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 9.2.c: *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.

References

Brendan B. Larsen, Elizabeth C. Miller, Matthew K. Rhodes, and John J. Wiens, "Inordinate Fondness Multiplied and Redistributed: the Number of Species on Earth and the New Pie of Life," The Quarterly Review of Biology 92, no. 3 (September 2017): 229-265. DOI

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9.3: Genetic Diversity

In contrast to ecosystem and species diversity, **genetic diversity** is a measure of the variability among individuals within a single species. Genetic diversity is represented by the variety of alleles present within a population. A **gene** represents the fundamental physical unit of heredity, and **alleles** are specific versions of these genes. For example, there is a gene for flower colors in peas, one allele for that gene carries information for white flowers while another allele carries information for purple flowers. Alleles are passed from parent to offspring. **Mutations**, changes in the DNA sequences that usually result from errors during DNA replication, are the original source of new alleles.

As a result of sexual reproduction, individuals can have different allele combinations for each gene. Genetic diversity provides the raw material for **evolutionary adaptation**, the process by which the genetic composition of populations change over time in a way that makes it more suited to the environment.

Loss of genetic diversity makes a species less able to reproduce successfully and less adaptable to a changing environment or to a new disease. Small populations of species are especially susceptible to loss of genetic diversity. When a species loses too many individuals, it becomes genetically uniform. Some of the causes for the loss in genetic diversity include: **inbreeding** among closely related individuals and **genetic drift**, the process by which the genetic composition of a population fluctuates randomly over time.

Low genetic diversity makes the Tasmanian devil (figure $9.3.a$) especially vulnerable to Devil Facial Tumor Disease (DFTD), a cancer that threatens it with extinction. Contagious cancers are typically spread by viruses, which can transmit cancer-causing genes; however, in the case of DFTD, the cancerous cells themselves are spread among individuals. Usually, the immune system can recognize cancerous cells, infected cells, and foreign cells, but DFTD cells evade the immune system. If Tasmanian devils had high genetic diversity, it is likely that some individuals would have alleles that made them resistant to DFTD. These individuals would survive and reproduce more frequently than others, and the resistant alleles would become more common in the population (evolutionary adaptation would occur). Because Tasmanian devils have low genetic diversity, there is less opportunity for such evolutionary adaptation.

Figure $9.3.a$: The Tasmanian devil in a defensive stance, at Tasmanian Devil Conservation Park, Tasman Peninsula. Image by Wayne McLean (CC-BY-SA).

Genetic diversity is important to agriculture. 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.

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 (figure $9.3.b$). 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.

Figure $9.3.b$: The effects of potato blight, which is cause by the water mold *Phytophthora infestans*. Image by USDA (public domain).

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 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 $9.3.c$) 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.

Figure 9.3.c: The Svalbard Global Seed Vault is a storage facility for seeds of Earth's diverse crops. (credit: Mari Tefre, Svalbard Global Seed Vault)

Supplemental Reading

Dunlap, Garrett. 2018. Facing Facts: Why a transmissible facial cancer is decimating Tasmanian devil populations. SITN Blog. The Graduate School of Arts and Sciences. Harvard University.

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9.4: Patterns of Biodiversity

Biodiversity is not evenly distributed on the planet. For example, Lake Victoria in Africa (figure $9.4.a$) contained almost 500 species from a family of fishes called cichlids before the introduction of the **invasive** Nile Perch in the 1980s and 1990s caused a mass extinction. (Note that this number does not include species of other fish families.) Lake Huron, the second largest of North America's Great Lakes, 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.

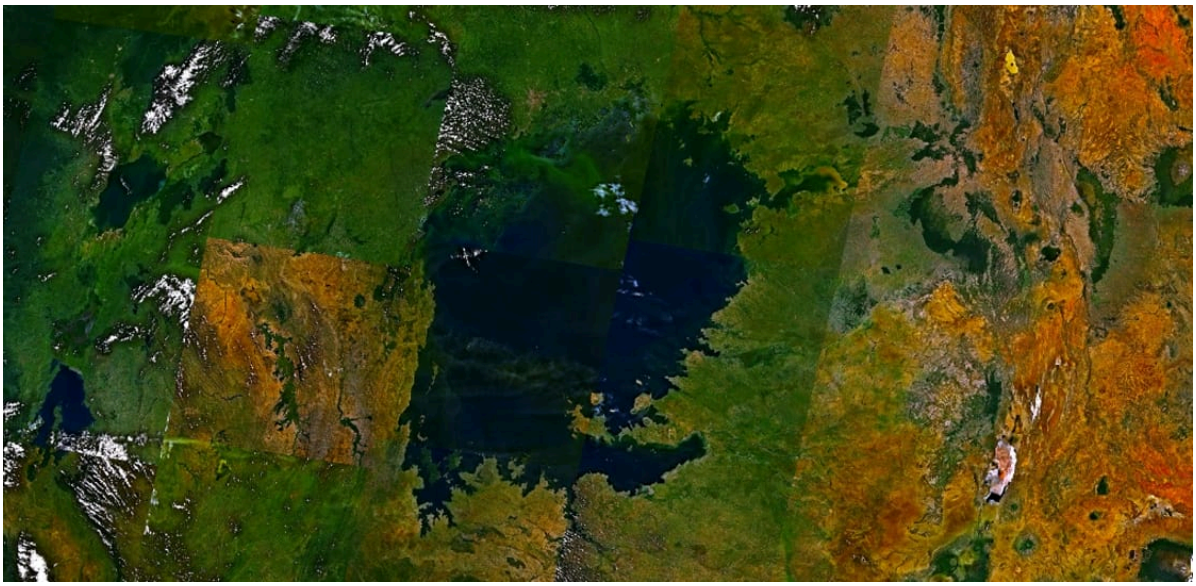

Figure $9.4.a$: Lake Victoria in Africa, shown in this satellite image, was the site of one of the most extraordinary evolutionary findings on the planet, as well as a casualty of devastating biodiversity loss. (credit: modification of work by Rishabh Tatiraju, using NASA World Wind software)

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 subfields 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.

The Tropics Have High Biodiversity

One of the oldest observed patterns in ecology is that biodiversity typically increases as latitude declines. In other words, the greatest species richness occurs near the equator and the lowest richness occurs near the poles (figure $9.4.b$).

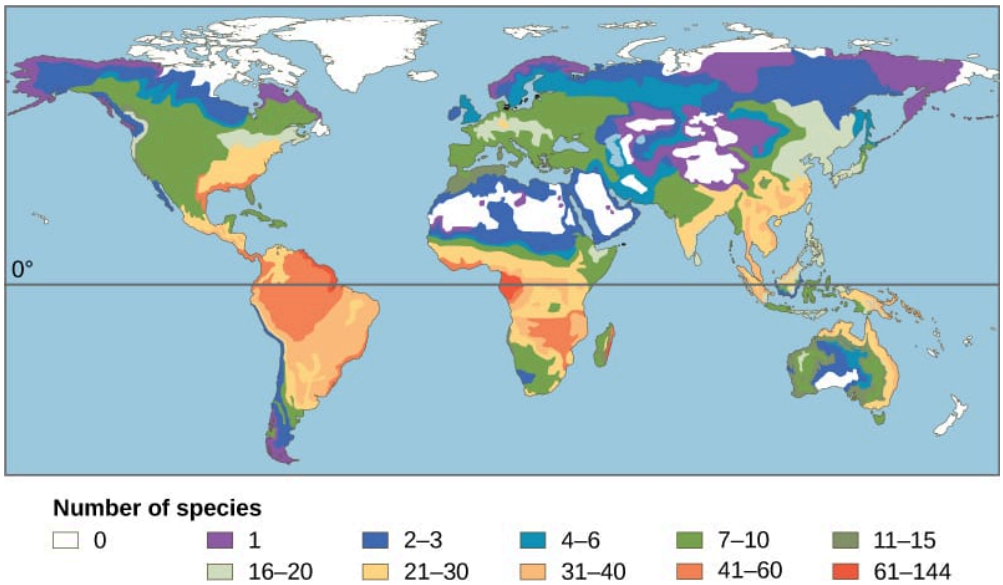

Figure $9.4.b$: This map illustrates the number of amphibian species across the globe and shows the trend toward higher biodiversity at lower latitudes. A similar pattern is observed for most taxonomic groups. The greatest number of species, 61-144, are found in the Amazon region of South America and in parts of Africa. Between 21 and 60 species are found in other parts of South America and Africa, and in the eastern United States and Southeast Asia. Other parts of the world have between 1 and 20 amphibian species, with the fewest species occurring at northern and southern latitudes.

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

Biodiversity Hotspots

In 1988, British environmentalist Norman Myers developed a conservation concept to identify geographical areas rich in species and at significant risk for species loss: **biodiversity hotspots**. The original criteria for a hotspot included the presence of 1500 or more endemic plant species and 70 percent of the area disturbed by human activity. **Endemic species** are found in only one location. For example, all of cichlid species found in Lake Victoria only occurred there. The blue jay is endemic to North America, while the Barton Springs salamander is endemic to the mouth of one spring in Austin, Texas. Endemic species with highly restricted distributions, like the Barton Springs salamander, are particularly vulnerable to extinction. If a population of a widespread species declines in one region, individuals from another region may be able to recolonize the first location, but this is not possible for endemic species. Endemic species are particularly common in isolated regions, such as mountaintops or islands. Endemism is especially likely on islands that are large and far from the mainland. Identifying biodiversity hotspots aids with conservation efforts, a kind of conservation triage. By protecting hotspots, governments are able to protect a larger number of species. There are now 34 biodiversity hotspots (figure $9.4.c$) containing large numbers of endemic species, which include half of Earth's endemic plants.

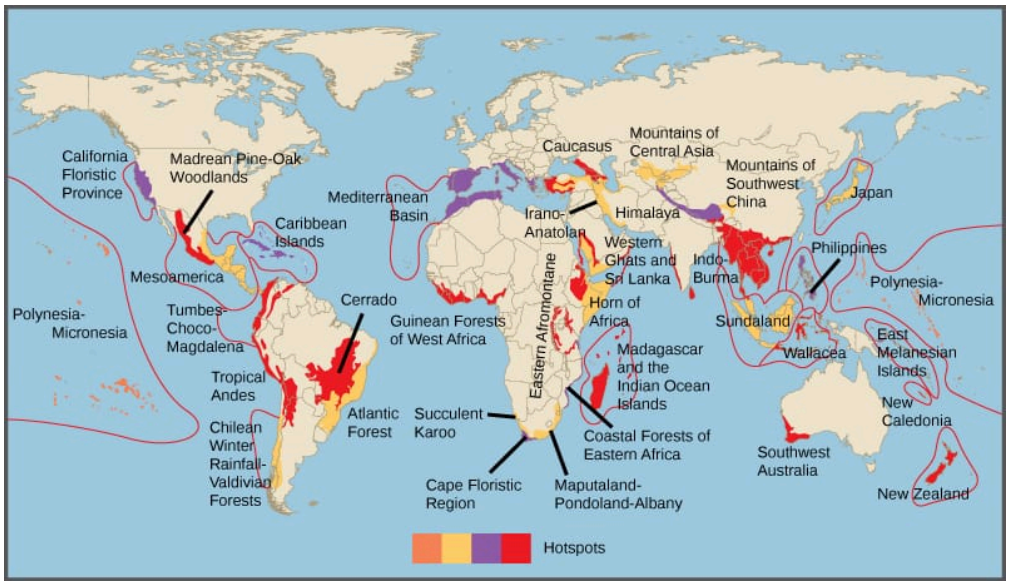

Figure $9.4.c$: Conservation International has identified 34 biodiversity hotspots, which cover only 2.3 percent of the Earth's surface but have endemic to them 42 percent of the terrestrial vertebrate species and 50 percent of the world's plants. Hotspots are shaded in red, purple, yellow, or orange. Examples include the California Floristic Province, Tropical Andes, Mediterranean Basic, Cape Floristic Province, and Polynesia-Micronesia.

Biodiversity Hotspots in South Africa

A rich species diversity is found in South Africa. With a land surface of approximately 148,000 km^2 (about 57,000 square miles), representing approximately 1% of the Earth's total surface, South Africa contains 10% of the world's total known bird, fish and plant species, and 6% of the world's mammal and reptile species.

This natural wealth is threatened by the expansion of the human population and the increasing demand this places on the environment. The Karoo (figure $9.4.d$) and the Cape are biodiversity hotspots in South Africa. South Africa has a wide range of climatic conditions and many variations in landscape, creating a variety of ecological niches, which can promote species diversity. These various landscapes give rise to the biomes which allow a wide variety of life to survive.

Figure $9.4.d$: Map of South Africa, illustrating the Karoo, a dry region with hot summers and cold winters. Image by (WT-shared) NJR ZA at wts wikivoyage (CC-BY-SA).

More than 20,300 species of flowering plants occur in South Africa (figure $9.4.e$). One of the six most important areas of plant growth in the world is in the Western Cape. Most of the 2,000 threatened species of plants are found in the **fynbos** in South-West Cape (figure $9.4.f$).

Figure $9.4.e$: Vegetation of the Karoo in near Willowmore, Eastern Cape, South Africa. Image by Winfried Bruenken (CC-BY-SA).

Figure $9.4.f$: Vegetation of the fynbos in Western Cape, South Africa. Image by Joachim Huber (CC-BY-SA).

South Africa is home to 243 mammal species. Among the 17 threatened species in South Africa are the black rhino, pangolin, and giant golden mole. The blue antelope and quagga (figure $9.4.g$) have become extinct. Of more than 800 bird species, 26 are threatened, including the penguin, Cape vulture, martial eagle (figure $9.4.h$), and Cape parrot. In total 370 reptiles and amphibians occur in the region of which 21 are threatened. Six of these are endangered. Of the 220 freshwater fishes in South Africa, 21 are threatened. There are more than 2,000 marine fish species. While many insect species remain unidentified, 80,000 insects are known to occur.

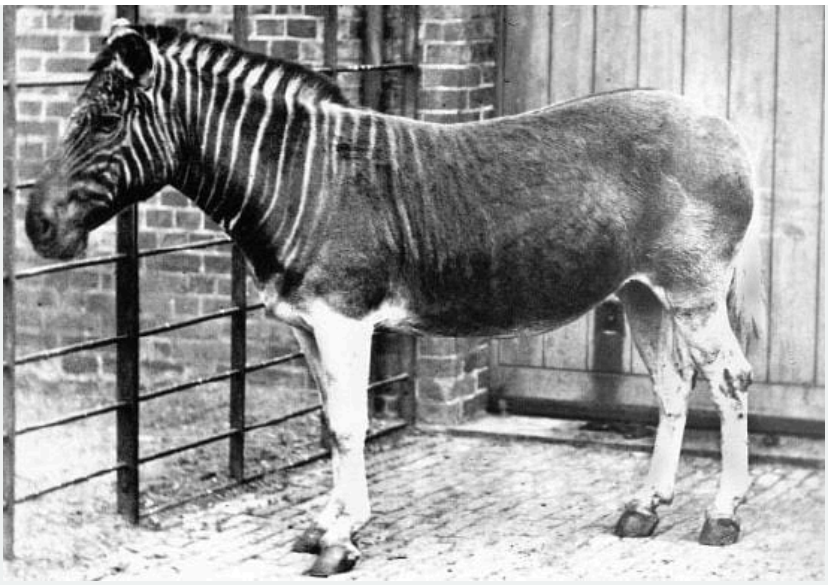

Figure $9.4.g$: The quagga (*Equus quagga quagga*), now extinct, is technically a subspecies of the plains zebra. Image by Stanford Woods (public domain).

Figure $9.4.h$: The Martial Eagle (*Polemaetus bellicosus*) is one of the threatened bird species found in South Africa. Image by Charles J. Sharp (CC-BY-SA).

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Spatial and Temporal Heterogeneity Promote Biodiversity

Environmental heterogeneity refers to the lack of uniformity in an area. Regions that are spatially heterogeneous are composed of smaller areas with contrasting vegetation, water and nutrient availability, soils and rocks, or other features. In regions that are temporally heterogeneous, conditions fluctuate over time. Heterogeneity promotes species richness by increasing the number of ecological niches, and heterogenous regions are thus priorities with respect to conserving biodiversity. Some regions are more hetergeneous than others. For example, a wetland consists of many microhabitats that differ in soil type and water availability, and water levels change over the seasons. Other regions, like the temperate grasslands in the midwestern United States, are relatively homogenous (uniform). Just as biodiversity can be assessed at a variety of scales, heterogeneity can be measured at large scales (such as within an entire biome) or small scales (such as within a single meadow).

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9.5: Data Dive- Biodiversity and Drugs

Overview

Global biodiversity continues to contribute significantly to the production of drugs. A 2016 paper reviewed drug sources for both synthetic and natural categories from 1981 to 2014. The figure below below displays the categories used in the analysis and a graph breaking down their results:

- “B”: Biological macromolecule
- “N”: Unaltered natural product, however, could have been semi- or totally synthetic
- “NB”: Natural product “botanical drug”
- “ND”: Natural product derivative
- “S”: Synthetic drug
- “S*”: Synthetic drug (NP pharmacophore)
- “V”: Vaccine
- “S-VM”: Natural product mimic of “S”
- “S*-VM”: Natural product mimic of “S*”

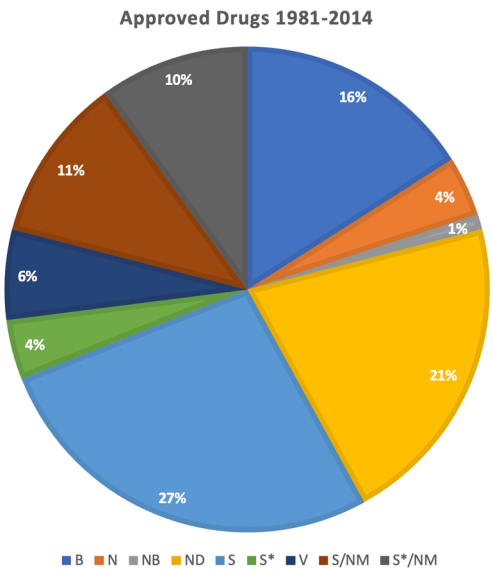

Figure $9.5.a$: Percent of drugs approved between 1981 and 2004 with either a synthetic or natural sub-classification. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Newman DJ and Cragg GM 2016.

Questions

1. What question(s) are the authors trying to answer with this graph?
2. What are the top three largest approved drug categories?
3. After reading over the categories outlined, provide your impression/reflection for all the categories that were identified.
4. What reason could you provide as to why the N and NB categories are so small compared to ND?
5. Do you think the results of this graph can be used as a defense of saving/conserving biodiversity now and into the future? Why?

Raw Data From Above Graph(s)

Table $9.5.a$: Raw data for percent of drugs approved between 1981 and 2004 with either a synthetic or natural sub-classification. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Newman DJ and Cragg GM 2016.

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9.6: Review

Summary

After completing this chapter you should be able to...

- Define biodiversity.
- Distinguish among ecosystem, species, and genetic diversity, explaining the value of each.
- Define and provide examples of ecosystem services.
- Distinguish between species richness and species evenness.
- Provide an approximate estimate of the number of species on Earth as well as the percentage of species that have been identified.
- Explain the criteria for biodiversity hotspots and their role in conservation.
- Identify the characteristics of endemic species.
- Summarize hypotheses explaining high biodiversity near the equator.

Biodiversity exists at multiple levels of organization and is measured in different ways depending on the goals of those taking the measurements. These measurements include **ecosystem diversity**, **species diversity**, and **genetic diversity**. The number of described species is estimated to be 1.5 million with about 17,000 new species being described each year. Estimates for the total number of species on Earth vary but are on the order of 10 million. Biodiversity is negatively correlated with latitude for most taxa, meaning that biodiversity is higher in the tropics. The mechanism for this pattern is not known with certainty, but several plausible hypotheses have been advanced.

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10: THREATS TO BIODIVERSITY

Chapter Hook

The northern spotted owl (*Strix occidentalis caurina*) is a western North American owl species that prefers large swaths of pristine old growth forests (that typically take 150-200 years to mature) for nesting. Unfortunately, most western forests have been regularly harvested for timber since around the establishment of the Forest Service in 1905. Thus, this species preferred habitat has been largely destroyed and their populations have plummeted. Habitat destruction is the number one cause for species extinction globally. For some species that are very habitat specific, like the northern spotted owl, there are not as many conservation actions to choose from that can help reverse declining population trends.

Figure $10.a$ Northern spotted owl perched in a tree. Image by USFS (licensed under CC-BY 2.0)

Biodiversity loss refers to the reduction of biodiversity due to displacement or extinction of species. The loss of a particular individual species may seem unimportant to some, especially if it is not a charismatic species like the Bengal tiger or the bottlenose dolphin. However, biologists estimate that species extinctions are currently many times higher the normal, or background, rate seen previously in Earth's history. This translates to the loss of tens of thousands of species within our lifetimes. This is likely to have dramatic effects on human welfare through the collapse of ecosystems. Loss of biodiversity may have reverberating consequences on ecosystems because of the complex interrelations among species. For example, the extinction of one species may cause the extinction of another. To measure biodiversity loss, scientists assess which species are at risk of extinction as well as survey ecosystem decline.

The core threat to biodiversity on the planet is the combination of human population growth and the resources used by that population. The human population requires resources to survive and grow, and many of those resources are being removed unsustainably from the environment. The five main threats to biodiversity are habitat loss, pollution, overexploitation, invasive species, and climate change. Increased mobility and trade has resulted in the introduction of invasive species while the other threats are direct results of human population growth and resource use.

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- Threats to Biodiversity

10.1: Extinction

10.2: Measures of Biodiversity Loss

10.3: Habitat Loss

10.4: Overexploitation

10.5: Pollution

10.6: Invasive Species

10.7: Climate Change

10.8: Data Dive- Threats to Biodiversity

10.9: Review

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10.1: Extinction

Speciation and Extinction

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. **Speciation** occurs when new species evolve, and **extinction** is the global loss of a species. When speciation rates begin to outstrip extinction rates, the number of species will increase; likewise, the number of species will decrease when extinction rates begin to overtake speciation rates. Throughout Earth's history, these two processes have fluctuated—sometimes leading to dramatic changes in the number of species on Earth as reflected in the fossil record (Figure $10.1.a$).

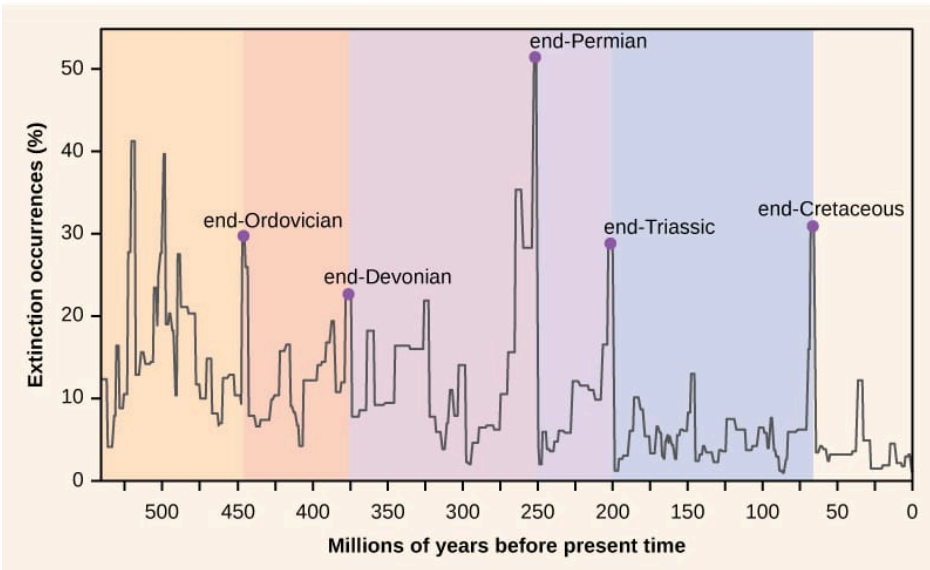

Figure $10.1.a$: Percent extinction occurrences as reflected in the fossil record have fluctuated throughout Earth's history. This graph shows the extinction occurrences as a percentage over time (in millions of years before present time). At the lowest points on the cycle, extinction occurrences were between 2% and 5% percent. Sudden and dramatic losses of biodiversity, called mass extinctions, have occurred five times, marking the end of geological periods: end-Ordovician, 450 million years ago; end-Devonian, 374 million years ago; end-Permian, 252 million years ago; end-Triassic, 200 million years ago; and end-Cretaceous, 65 million years ago. During these spikes, extinction occurrences approximately ranged from 22% to 50%.

Mass Extinctions

Paleontologists have identified five events in geological history of sudden and dramatic losses in biodiversity, with more than half of all extant species disappearing from the fossil record. **Extant** species are those that are surviving (not extinct) at a point in time. These five events are called mass extinctions. There are many lesser, yet still dramatic, extinction events, but the five mass extinctions have attracted the most research. An argument can be made that the five mass extinctions are only the five most extreme events in a continuous series of large extinction events that have occurred since 542 million years ago.

The fossil record of the mass extinctions was the basis for defining periods of geological history, so they typically occur at the transition point between geological periods. The transition in fossils from one period to another reflects the dramatic loss of species and the gradual origin of new species. These transitions can be seen in the rock layers. Table $10.1.a$ provides the names and dates of the five mass extinctions.

In most cases, the hypothesized causes are still controversial; however, the causes of the most recent event, the end-Cretaceous extinction, are best understood (table $10.1.a$). It was during this extinction event 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 (55 lbs) 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. Biodiversity

recovery times after mass extinctions vary, but have been up to 30 million years.

Table $10.1.a$***:*** *Summary of the five mass extinctions, including the name, dates, percent of biodiversity lost, and hypothesized causes.*

Geological Period	Mass Extinction Name	Time (millions of years ago)	Loss in Biodiversity	Hypothesized Cause(s)
Ordovician–Silurian	end-Ordovician O–S	450–440	85% of marine species	Global cooling and then warming, gamma-ray burst from supernova removed ozone layer
Late Devonian	end-Devonian	375–360	79-87% of all species	Unknown
Permian–Triassic	end-Permian	251	96% of marine species and 70% of terrestrial (land) species	Volcanic activity, decrease on dissolved oxygen in the oceans
Triassic–Jurassic	end-Triassic	205	76% of all species	Climate change, asteroid impact, volcanic eruptions
Cretaceous–Paleogene	end-Cretaceous K–Pg (K–T)	65.5	50% of animals and plants	Asteroid impact

The Pleistocene Extinction is one of the lesser extinctions, and a recent one. It is well known that the North American, and to some degree Eurasian **megafauna**, or large animals, disappeared toward the end of the last glaciation (cooling) period. The extinction appears to have happened in a relatively restricted time period of 10,000–12,000 years ago. In North America, the losses were quite dramatic and included the woolly mammoths (last dated about 4,000 years ago in an isolated population), mastodon, giant beavers, giant ground sloths, saber-toothed cats, and the North American camel, just to name a few. The possibility that the rapid extinction of these large animals was caused by overhunting, a type of overexploitation, was first suggested in the 1900s. Research into this hypothesis continues today. It seems likely that overhunting caused many pre-written history extinctions in many regions of the world.

The Sixth Mass Extinction

The sixth, or Holocene, mass extinction appears to have begun earlier than previously believed and has mostly to do with the activities of *Homo sapiens*. Since the beginning of the Holocene period, 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 (figure $10.1.b$). It was hunted for its meat by sailors and was easy prey because the dodo, which did not evolve with humans, would approach people without fear. Introduced pigs, rats, and dogs brought to the island by European ships also killed dodo young and eggs.

Figure $10.1.b$: 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 first discovered by Europeans in 1741 and was hunted for meat and oil. The last sea cow was killed in 1768. That amounts to 27 years between the sea cow's first contact with Europeans and extinction of the species.

In 1914, the last living passenger pigeon died in a zoo in Cincinnati, Ohio. This species had once darkened the skies of North America during its migrations, but it was hunted and suffered from habitat loss through the clearing of forests for farmland. In 1918, the last living Carolina parakeet died in captivity. This species was once common in the eastern United States, but it suffered from habitat loss. The species was also hunted because it ate orchard fruit when its native foods were destroyed to make way for farmland. The Japanese sea lion, which inhabited a broad area around Japan and the coast of Korea, became extinct in the 1950s due to fishermen. The Caribbean monk seal was distributed throughout the Caribbean Sea but was driven to extinction via hunting by 1952.

As described in the next section, the current high rates of extinction will cause a large and rapid decline in the biodiversity of the planet. According to a 2019 United Nations report, 1 million species are at risk of extinction. Considering there are estimated to be 8-11 million species total (see The Number of Species on Earth), that means up to 12.5% of species could go extinct, and many of them within our lifetimes.

Estimates of Present-Time Extinction Rates

The **background extinction rate** is estimated to be about 1 extinction per million species each year (E/MSY). For example, if there are 8-11 million species in existence, then we would expect 8-11 of those species to become extinct in a year.

Estimates of extinction rates are hampered by the fact that most extinctions are probably happening without observation. One contemporary extinction-rate estimate uses the extinctions in the written record since the year 1500. For birds alone, this method yields an estimate of 26 E/MSY, almost three times the background rate. However, this value may be underestimated for three reasons. First, many existing species would not have been described until much later in the time period and so their loss would have gone unnoticed. Second, we know the number is higher than the written record suggests because now extinct species are being described from skeletal remains that were never mentioned in written history. And third, some species are probably already extinct even though conservationists are reluctant to name them as such. Taking these factors into account raises the estimated extinction rate to nearer 100 E/MSY. The predicted rate by the end of the century is 1500 E/MSY.

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 $10.1.c$). 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. Species–area estimates have led to estimates of present-day species extinction rates of about 1000 E/MSY and higher.

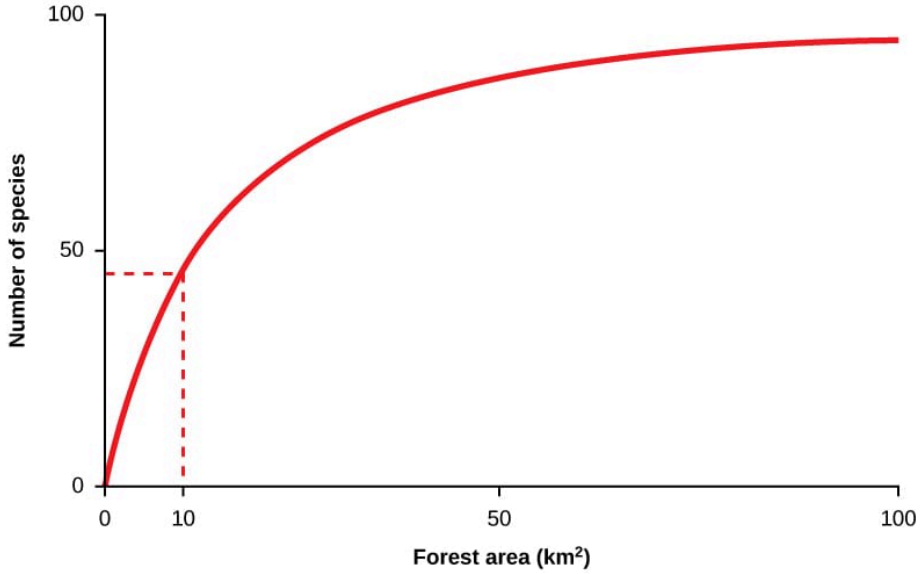

Figure 10.1.c: A typical species-area curve shows the cumulative number of species found as more and more area is sampled. The curve has also been interpreted to show the effect on species numbers of destroying habitat; a reduction in habitat of 90 percent from 100 km^2 to 10 km^2 reduces the number of species supported by about 50 percent.

Many extinctions will affect species that biologists have not yet discovered. Most of these "invisible" species that will become extinct currently live in tropical rainforests (figure 10.1.d). These rainforests are the most diverse ecosystems on the planet and are being destroyed rapidly by deforestation to provide timber and space for agriculture.

Figure 10.1.d: 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)

Extirpation

The elimination of species at a local level–known as **extirpation** – also poses threats to the integrity and sustainability of ecosystems. Widespread extirpation can obviously lead to extinction, but absence of species, even at a local scale, can affect ecosystem function. For example, by the mid-1920s wolves had been extirpated from Yellowstone National Park, although

they continued to thrive elsewhere. When wolves were reintroduced to the park in the mid-1990s, they regulated elk populations, benefiting the vegetation and plant communities (see Ecosystem Restoration). What mattered for ecosystem function in Yellowstone was whether wolves were present there, not just whether the species survived somewhere.

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10.2: Measures of Biodiversity Loss

The Red List

The **International Union for the Conservation of Nature (IUCN)** coordinates efforts to catalog and preserve biodiversity worldwide. One way scientists gauge trends in biodiversity is by monitoring the fate of individual species. Since 1964, the IUCN has compiled information in the Red List of Threatened Species, which includes plants, animals, fungi, and selected brown algae species. Updates to the Red List are released every four years.

Species can be classified into nine Red List categories based on their extinction risk. Firstly, there are species that are already **extinct** and those that are **extinct in the wild**, meaning that the remaining individuals are only found in captivity. Species at risk of extinction are called **threatened**. Species that are at risk of becoming threatened are called **near threatened**. The Emperor Penguin (*Aptenodytes forsteri*) is an example a near threatened species, mainly due to habitat loss and climate change (figure $10.2.a$). Those with little risk of extinction are designated **least concern**. Note that only a fraction of the 8-11 million species on Earth are identified (see The Number of Species on Earth). For many of the species that are identified, data still needs to be gathered before they can be assigned to a Red List category (**data deficient**). Less than 10% of the approximately 1.5 million identified species have been assessed for the Red List at all. Species that have not been assessed are deemed **not evaluated**.

Figure $10.2.a$: The Emperor Penguin is an example of near threatened species. Image by Christopher Michel (CC-BY).

There are three categories of threatened species: **vulnerable, endangered,** and **critically endangered**. Of these, critically endangered species have the greatest risk while vulnerable species are at the least risk out of the threatened categories. The African elephant (*Loxodonta africana*) is listed vulnerable species due to poaching and habitat loss (figure $10.2.b$). Interestingly, the forest subspecies (*L. africana cylotis*) is at much greater risk than the savanna subspecies (*L. africana africana*), but the Red List category is assigned at the species level in this case. The blue whale (*Balaenoptera musculus*) is endangered due to pollution, climate change, and poaching (figure $10.2.c$). Fortunately, blue whale population size is increasing. Several species of pitcher plants, which trap insects as a source of nitrogen, are critically endangered due to overexploitation and habitat loss (figure $10.2.d$).

Figure $10.2.b$: The African forest elephant (*Loxodonta africana cylotis*) is at greater risk of extinction than the savanna subspecies. When both subspecies are grouped together, African elephants are considered vulnerable. Image by Peter H. Wrege (CC-BY-SA).

Figure $10.2.c$: The blue whale (*Balaenoptera musculus*) is categorized as endangered according to the IUCN Red List. Image by Mike Baird (CC-BY).

Figure $10.2.d$: *Nepenthes aristolochioides* is a critically endangered pitcher plant. Image by Alfindra Primaldhi (CC-BY).

Extinct and Threatened Animals

Scientists know much more about the state of **vertebrates**—especially mammals, birds, and amphibians—than they do about other forms of animal life. Of 6,594 described mammal species, 96 species have become extinct during the last 500 years (Mammal Diversity Database). According to the Red List, approximately 26% of mammal species worldwide are known to be threatened. A smaller percentage (about 14%) of the world's 10,721 identified bird species (Birds of the World) are threatened (figure $10.2.e$).

Figure $10.2.e$: North American passenger pigeons lived in enormous flocks and were once the most numerous birds on earth. Market hunting on a massive scale and habitat destruction combined to extinguish them as a species in the early twentieth century. Image by James St. John (CC-BY).

Among the well-studied vertebrates, amphibians are faring especially poorly. Of the more than 6,000 known species of amphibians, 35 have become extinct worldwide since 1500 (figure $10.2.f$), and two others are extinct in the wild (Red List). Overall, 41% of the world's amphibian species are known to be threatened (Red List). Only small proportions of the world's species of reptiles and fish have been evaluated for purposes of the Red List. Among those, 34% of selected reptiles and 8% of selected bony fishes are threatented (Red List).

Figure $10.2.f$: The extinct golden toad of Monteverde, Costa Rica, was last seen in 1989. Its extinction is attributed to fungal infection combined with especially hot, dry weather. Source: U.S. Fish and Wildlife Service via Wikimedia Commons

Invertebrates comprise the vast majority of animals, an estimated 97% of animal species. They include everything from insects and arachnids, to mollusks, crustaceans, corals, and more. Few of these groups have been assessed in a comprehensive way, but assessments within some groups call attention to disturbing, large-scale trends. For example, 33% of the world's reef-building corals are already considered threatened (Red List), and many more of them are experiencing rates of decline that move them toward threatened status (figure $10.2.g$). The demise of reef-building corals has magnified ecological impacts, since so much other marine life depends on them.

Figure $10.2.g$: Reef-formal corals, such this pink soft coral, are at high risk of extinction. Source: Linda Wade via National Oceanic & Atmospheric Administration (NOAA)

Ecosystem Loss and Alteration

Another way of gauging biodiversity involves assessment on the scale of ecosystems. The causes of wholesale losses of ecosystems are much the same as those driving extinction or endangerment of species, with habitat destruction and fragmentation being the primary agent. Worldwide, for example, the conversion of land to agriculture and cultivation have led to significant losses in grassland ecosystems. In North America, nearly 70% of the tallgrass prairie ecosystem (which once covered 142 million acres) has been converted to agriculture, and losses from other causes, such as urban development, have brought the total to about 90%. Current estimates indicate that agricultural activity and cultivation systems now cover nearly 25% of the Earth's surface

According to the United Nations Millennium Ecosystem Assessment, by the beginning of the 21st century, 15 of the world's 24 ecosystems, from rainforests to aquifers to fisheries, were rated in serious decline. For example, tropical rainforests, which are the habitats for nearly half of the world's plant and animal species, covered about 4 billion acres in past centuries, but only 2.5 billion acres remain and nearly 1% is being lost annually. Losses have been especially severe in the tropics of Africa and Southeast Asia. Current estimates indicate that about 50% of the world's wetland habitat has been lost. (Note that wetlands are a broad collection of many different ecosytem types.) The former extent of wetland habitats worldwide (fresh, brackish and salt) is difficult to determine but certainly exceeded a billion acres.

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10.3: Habitat Loss

Humans rely on technology to modify their environment and make it habitable. Other species cannot do this. Elimination of their habitat—whether it is a forest, coral reef, grassland, or flowing river—will kill the individuals in the species. Remove the entire habitat, and the species will become extinct, unless they are among the few species that do well in human-built environments. Habitat loss includes habitat destruction and habitat fragmentation.

Habitat Destruction

Habitat destruction occurs when the physical environment required by a species is altered so that the species can no longer live there. Human destruction of habitats accelerated in the latter half of the twentieth century. Consider the exceptional biodiversity of Sumatra: it is home to one species of orangutan, a species of critically endangered elephant, and the Sumatran tiger, but half of Sumatra's forest is now gone. The neighboring island of Borneo, home to the other species of orangutan, has lost a similar area of forest. Forest loss continues in protected areas of Borneo. The orangutan in Borneo is listed as endangered by the International Union for Conservation of Nature (IUCN), but it is simply the most visible of thousands of species that will not survive the disappearance of the forests of Borneo. The forests are removed for timber and to plant palm oil plantations (figure $10.3.a$). Palm oil is used in many products including food products, cosmetics, and biodiesel in Europe. According to Global Forest Watch, 9.7% of tree cover was lost globally from 2002 to 2019, and 9% of that occurred in Indonesia and Malaysia (where Sumatra and Borneo are located). Figure $10.3.b$ shows the average annual change in forest area around the world from 1990 to 2015.

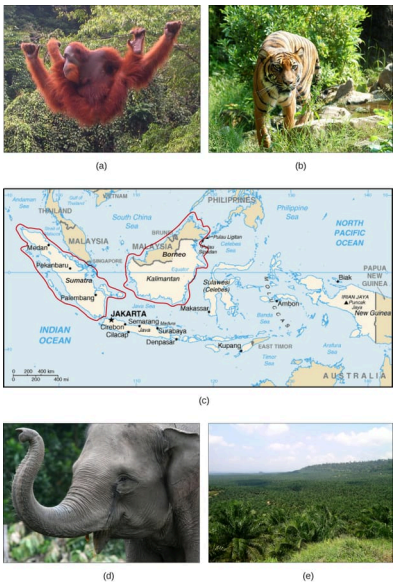

Figure $10.3.a$: (a) One species of orangutan, *Pongo pygmaeus*, is found only in the rainforests of Borneo, and the other species of orangutan (*Pongo abelii*) is found only in the rainforests of Sumatra. These animals are examples of the exceptional biodiversity of (c) the islands of Sumatra and Borneo, which are located in the south Pacific, just northwest of Australia. Sumatra is in the country of Indonesia. Half of Borneo is in Indonesia, and half is in Malaysia. Other species include the (b) Sumatran tiger (*Panthera tigris sumatrae*) and the (d) Sumatran elephant (*Elephas maximus sumatranus*), both critically endangered species. Rainforest habitat is being removed to make way for (e) oil palm plantations such as this one in Borneo's Sabah Province. (credit a: modification of work by Thorsten Bachner; credit b: modification of work by Dick Mudde; credit c: modification of work by U.S. CIA World Factbook; credit d: modification of work by "Nonprofit Organizations"/Flickr; credit e: modification of work by Dr. Lian Pin Koh)

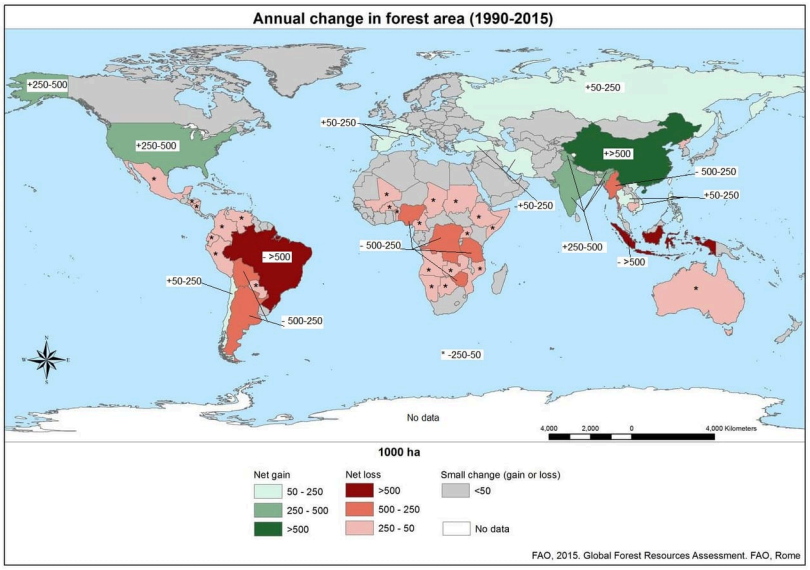

Figure $10.3.b$: Average annual change in forest area globally from 2005 to 2015. China is dark green, indicating that have gained more than 500 "kilohectares" (kha) of forest. Medium green indicates countries that have gained 250-500 kha, including the the United States, India, Ghutan, and Bangladesh. Light green indicates countries that have gained 50-250 khA, including Chile, Spain, France, Italy, Turkey, Iran, Russia, Vietnam, and Thailand. Indonesia and Brazil lost more than 500 kha of forest (marked with dark red). Countries that lost 500-250 kha are marked with medium red, including Bolivia, Argentina, Nigeria, Democratic Republic of the Congo, Tanzania, Zimbabwe, and Myanmar. Countries that lost 250-50 kha are marked with light red and an asterisk (*). These include Mexico, Honduras, Nicaragua, Venezuela, Colombia, Ecuador, Peru, Paraguay, Mali, Burkina Faso, Benin, Cameroon, Chad, Sudan, Ethiopia, Somalia, Uganda, Angola, Namibia, Botswana, Zimbabwe, Mozambique, Cambodia, North Korea, and Australia. No data has been collected for Antarctica. All other regions have had lost or gained less than 50 kha in forest area. Image by FAO, 2015. Global Forest Resources Assessment. FAO. Rome (Open Access Policy).

Preventing Habitat Destruction with Wise Wood Choices

Most consumers do not imagine that the home improvement products they buy might be contributing to habitat loss and species extinctions. Yet the market for illegally harvested tropical timber is huge, and the wood products often find themselves in building supply stores in the United States. One estimate is that up to 10% of the imported timber in the United States, which is the world's largest consumer of wood products, is illegally logged. A 2012 United Nations and Interpol report estimated that the illegal timber trade is worth $30-100 billion each year. 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 (figure $10.3.c$). Looking for their certification on flooring and other hardwood products is one way to ensure that the wood has not been taken illegally from a tropical forest. There are certifications other than the FSC, but these are run by timber companies, thus creating a conflict of interest. Another approach is to buy domestic wood species. While it would be great if there was a list of legal versus illegal woods, it is not that simple. Logging and forest management laws vary from country to country; what is illegal in one country may be legal in another. Where and how a product is harvested and whether the forest from which it comes is being sustainably maintained all factor into whether a wood product will be certified by the FSC. It is always a good idea to ask questions about where a wood product came from and how the supplier knows that it was harvested legally.

Figure $10.3.c$: The sawmill in Uaxactun, Guatamala is Forest Stewardship Council (FSC) certified and provides good income from a sustainable resource for not only the saw operators but also many others who help keep the operation running. Image by Jason Houston for USAID (public domain).

Habitat Destruction of Rivers and Streams

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

Habitat Fragmentation

Habitat fragmentation occurs when the living space of a species is divided into discontinuous patches. For example, a mountain highway could divide a forest habitat into separate patches. This is especially problematic for consumers at the top of the food chain, which require large ranges to find adequate prey. Additionally, habitat fragmentation separates individuals from potential mates. **Wildlife corridors** mitigate the damage of habitat fragmentation by connecting patches with suitable habitat. For example, the bridge over a highway could allow animals to move between habitat patches (figure $10.3.d$). Riparian areas, areas of land adjacent to bodies of water, such as streams, can serve as natural wildlife corridors when left intact.

Figure 10.3.d: This overpass on the Trans-Canada Highway between Banff and Lake Louise, Alberta, serves as a wildlife corridor. Image by WikiPedant at Wikimedia Commons (CC-BY-SA).

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10.4: Overexploitation

Overexploitation (overharvesting) involves hunting, fishing, or otherwise collecting organisms at a faster rate than they can be replenished.

Terrestrial Animals

Terrestrial animals may be overexploited as sources of food, garments, jewelry, medicine, or pets. For example, the poaching of elephants for their valuable ivory and rhinos for their horns, which are used in traditional medicine, is a major threat to these species. 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. Harvesting of pangolins for their scales and meat, and as curiosities, has led to a drastic decline in population size (figure $10.4.a$).

Figure $10.4.a$: Pangolins are threatened by overexploitation. This work by David Brossard is licensed under CC-BY.

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.

Aquatic Animals

Aquatic species are particularly vulnerable to overexploitation, which is more specifically called **overfishing** in this case. For about one billion people, aquatic resources provide the main source of animal protein (figure $10.4.b$), but since 1990, production from global **fisheries** (areas for catching wild or farmed fish or other aquatic animals) has declined. Figure $10.4.c$ illustrates the extent of overfishing in the U.S. Despite considerable effort, few fisheries are managed sustainability. For example, the western Atlantic cod fishery was a hugely productive fishery for 400 years, but the introduction of modern fishing vessels in the 1980s and the pressure on the fishery led to it becoming unsustainable. Bluefin tuna are in danger of extinction. The once-abundant Mediterranean swordfish fishery have been depleted to commercial and biological exhaustion.

Figure $10.4.b$: Fishing boats at marine fishers. 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

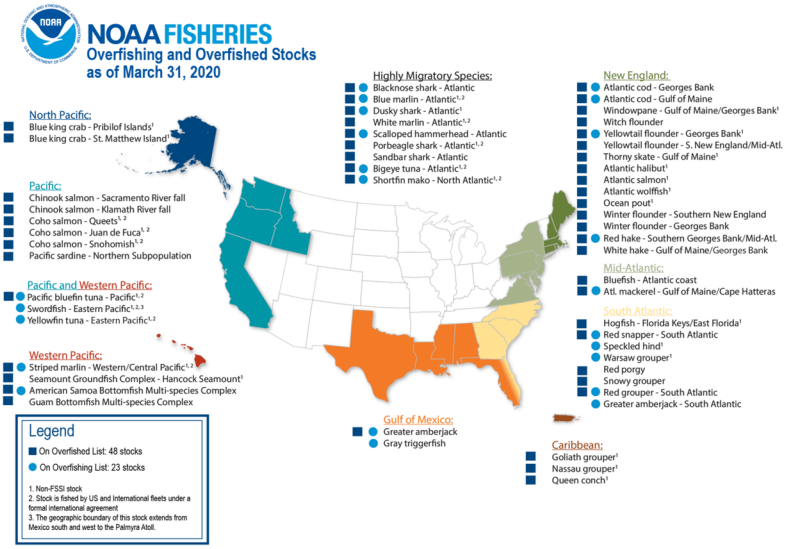

Figure $10.4.c$: Map of overfishing and overfished stocks in the U.S. by region. Stocks on the overfishing list are being harvested too quickly, and those on the overfished list have population sizes that are too low. For example, stocks of Chinook salmon, Coho salmon, and Pacific sardines are overfished in the Pacific. Some species, including stocks of Pacific bluefin tuna and Atlantic cod, are on both the overfishing and overfished lists. Image by NOAA (public domain).

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. This results on overexploitation. 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.

Overfishing can result in a radical restructuring of the marine ecosystem in which a dominant species is so overexploited that it no longer serves its ecological function. For example, overfishing a tertiary consumer could causes populations of secondary consumers to increase. Secondary consumers would then feed on primary consumes (like zooplankton), decreasing their population size. With fewer zooplankton, populations of primary producers (**phytoplankton**, or photosynthetic microorganisms) would be unregulated (see Food Chains). 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.

A related consequence of fishing practices is "**bycatch**," animals that fishers sometimes catch and discard because they do not want them, cannot sell them, or are not allowed to keep them. Bycatch can be fish, but also includes other animals such as dolphins, whales, sea turtles, and seabirds that become hooked or entangled in fishing gear.

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 4,000 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.

Plants and Fungi

Some plant and fungal species are also overexploited, particularly if they are slow-growing. For example, stocks of wild ginseng, which is valued for its health benefits, are dwindling. Peyote cactus, which causes hallucinations and is used in sacred ceremonies, is also declining. Yarsagumba, dead moth larvae that were infected by fungal parasites (caterpillar fungus, *Ophiocordyceps sinensis*), is overexploited because it is highly valued in traditional medicine and used as an aphrodisiac (figure $10.4.d$).

Figure $10.4.d$: Yarsagumba is a combination of moth larvae and the fungus that infected and killed it. Image by Punya (CC-BY-SA).

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10.5: Pollution

Pollution occurs when chemicals, particles, or other materials are released into the environment, harming the organisms there. For many thousands of years, ever since they built the first campfire, human activity has generated air, water, and soil pollution. For most of human history, however, these contaminants had relatively little environmental impact. But over the last few centuries, pollution levels skyrocketed due to population growth and the Industrial Revolution. As a result, regulations have been enacted to control emissions. Even where these are effective in curbing current pollution sources, high levels of contamination may exist from past activity. And new contamination can occur through industrial accidents or other inadvertent releases of toxic substances.

Pollution has contributed to the decline of many threatened species. For example, a 2007 study by Kingsford and colleagues found that pollution was a major pressure on 30% of threatened Red List species in Australia and surrounding regions.

Power plants, factories, and vehicles are common sources of air pollution. In some cases, the pollutants are directly toxic (for example, lead), but in other cases the pollutants indirectly cause ecological harm when they are present in unnaturally large quantities (for example, carbon dioxide emissions leading to climate change). Not only can air pollutants directly harm animals by causing respiratory issues and cancer as well as damage vegetation, but some interact with the atmosphere to form **acid deposition** (commonly called acid rain). Acid deposition disrupts aquatic ecosystems as well as soil communities and plant growth.

Heavy metals, plastics, pesticides, herbicides, fertilizers, and sediments are examples of water pollution. Heavy metals (including copper, lead, mercury, and zinc) can leach into soil and water from mines. Furthermore, **acid mine drainage** is caused by reaction of mine wastes, such as sulfides, with rainfall or groundwater to produce acids, like sulfuric acid. The Environmental Protection Agency estimates that 40% of the watersheds in the western United States are contaminated by mine run-off. Plastics harm shorebirds, turtles and aquatic invertebrates that ingest and accumulate them. Nutrients, such as nitrate and phosphates, are healthy in bodies of water to an extent, but when fertilizer pollution adds too many of these nutrients at one time, algal blooms can result. This has cascading effects that can ultimately shade and kill aquatic plants and deplete oxygen needed by fish and other animals (**eutrophication**). A particularly concerning water pollution problem is **micropollutants**. For examples, some chemical residues affect growth, cause birth defects, and have other toxic effects on humans and other organisms even at very low concentrations.

Figure $10.5.a$ summarizes the effects of air and water pollution on biodiversity, and the chapters about Solid Waste Management, Water Pollution, and Air Pollution explain these threats in more detail.

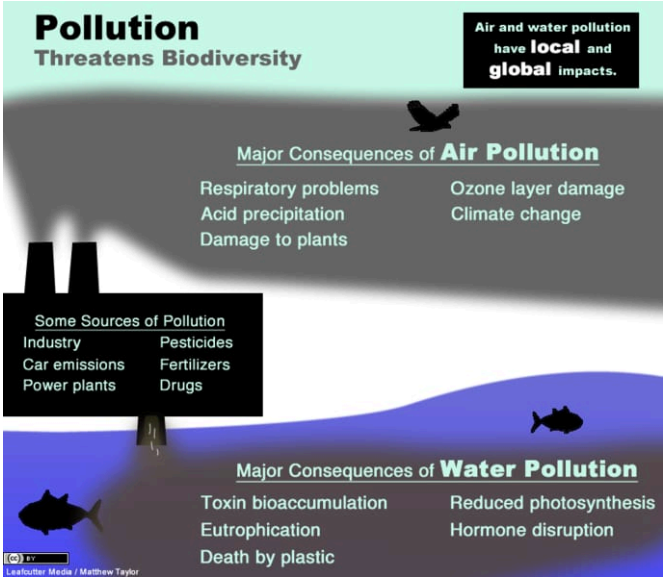

Figure $10.5.a$: Some sources of water and air pollution and their major effects on biodiversity. Sources of pollution include industry, car emissions, power plants, pesticides, fertilizers, and drugs. Some major consequences of air pollution include respiratory problems, acid precipitation, plant damage, ozone depletion, and climate change. Water pollution can bioaccumulate and can lead to eutrophication, death by plastic, reduced photosynthesis, and hormone disruption. Image by Leafcutter Media (CC-BY-SA).

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10.6: Invasive Species

Invasive species are non-native organisms that, when introduced to an area out of its native range, disrupt the community they invade. **Non-native** (exotic) refers to species occurring outside of their historic distribution. Invasive species 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. Invasive species can cause ecological and economic damage. They threaten other species through competition for resources, predation, or disease.

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*; figure $10.6.a$). Whether enjoying a forest hike, taking a summer boat trip, or simply walking down an urban street, you have likely encountered an invasive species.

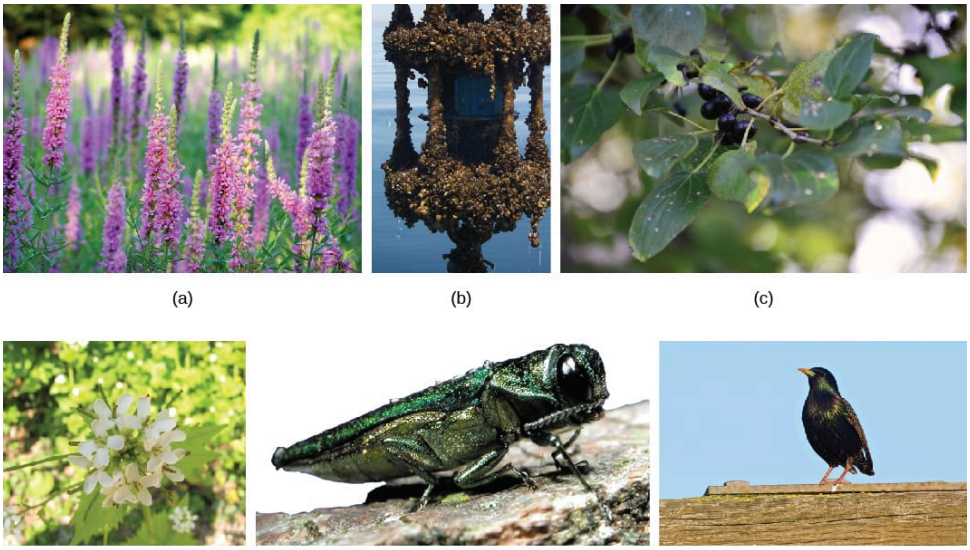

Figure $10.6.a$: In the United States, invasive species like (a) purple loosestrife (*Lythrum salicaria*) and the (b) zebra mussel (*Dreissena polymorpha*) threaten certain aquatic ecosystems. Some forests are threatened by the spread of (c) common buckthorn (*Rhamnus cathartica*), (d) garlic mustard (*Alliaria petiolata)*, and (e) the emerald ash borer (*Agrilus planipennis*). The (f) European starling (*Sturnus vulgaris*) may compete with native bird species for nest holes. (credit a: modification of work by Liz West; credit b: modification of work by M. McCormick, NOAA; credit c: modification of work by E. Dronkert; credit d: modification of work by Dan Davison; credit e: modification of work by USDA; credit f: modification of work by Don DeBold)

Asian Carp

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 (those that historically occurred in the area and are adapted to the local ecosystem) for these resources and alters 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.

Effect on Endemic 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 (see Patterns of Biodiversity). The accidental introduction of the brown tree snake via aircraft (figure $10.6.b$) 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 $10.6.b$: 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)

Introduction by Ballast Water

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

Invasive Species as Diseases

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* (Bd), which causes the disease chytridiomycosis (figure $10.6.c$). 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 disease **reservoir** by storing the infectious fungus.

Figure $10.6.c$: 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 $10.6.d$). 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 $10.6.d$: 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).

Biological Control of Invasive Species

One reason why invasive species proliferate dramatically outside of their native range is due to **release from predators**. This means that parasites, predators, or herbivores that usually regulate their populations are not present, allowing them to outcompete or overpredate native species, which are still regulated. Based on this principle, organisms that regulate the invasive species populations have been introduced to the newly colonized areas in some cases. The release of organisms (or viruses) to limit population size is called **biological control**. As described in the examples below, biological control of invasive species has had varying success, exacerbating the problem in some cases and solving it in others.

Prickly-pear Cactus (*Opuntia*)

Introduced into Australia, this cactus soon spread over millions of hectares of range land driving out forage plants. In 1924, the cactus moth, *Cactoblastis cactorum*, was introduced (from Argentina) into Australia. The caterpillars of the moth are voracious feeders on prickly-pear cactus, and within a few years, the caterpillars had reclaimed the range land without harming a single native species. However, its introduction into the Caribbean in 1957 did not produce such happy results. By 1989, the cactus moth had reached Florida, and now threatens five species of native cacti there.

Purple Loosestrife

The leaf beetle (*Galerucella calmariensis*) has been introduced to suppress purple loosestrife, a noxious weed (figure $10.6.e$). A combination of four biological controls, including the leaf beetle were released in Minnesota since 1992. While it has not eradicated populations of this invasive species, biological control largely removed leaves from 20% of the purple loosestrive populations where it was released, which could reduce competition for native species. The biological controls established populations in most locations where they were released and even spread to new patches of purple loosestrife.

Figure $10.6.e$: 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.

Klamath Weed

In 1946 two species of *Chrysolina* beetles were introduced into California to control the Klamath weed (St. Johnswort) that was ruining millions of acres of range land in California and the Pacific Northwest. Before their release, the beetles were carefully tested to make certain that they would not turn to valuable plants once they had eaten all the Klamath weed they could find. The beetles succeeded beautifully, restoring about 99% of the endangered range land and earning them a commemorative plaque at the Agricultural Center Building in Eureka, California.

European Rabbit

In 1859, the European rabbit was introduced into Australia for sport. With no important predator there, it multiplied explosively (figure $10.6.f$). The raising of sheep (another imported species) suffered badly as the rabbits competed with them for forage.

Figure $10.6.f$: These rabbits in Australia removed all forage plants, which ordinarily supply them with water as well as food. They thus had to drink from a pool. Image by National Archives of Australia (public domain).

In 1950, the **myxoma virus** was brought from Brazil and released. The epidemic that followed killed off millions of rabbits (more than 99% of the population). Green grass returned, and sheep raising once again became profitable. Rabbit populations gradually increased, however, because the rabbits evolved to be more resistant to the virus, and the myxoma virus evolved to cause less damage. (Parasites, like viruses, benefit from multiplying inside the host and spreading to other individuals. If they kill their hosts too soon, they typically limit opportunities to multiply and spread.) More recently, the rabbit hemorrhagic disease virus has been used as biological control.

Strategies for Effective Biological Control

To summarize the lessons learned from biological control successes and failures, only candidates that have a very narrow target preference (eat only a sharply-limited range of hosts) should be chosen. Each candidate should be carefully tested to be sure that once it has cleaned up the intended target, it does not turn to desirable species. Biological controls must not be used against native species. Finally, introduction of non-native species into the environment should be avoided because they could themselves be invasive.

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10.7: Climate Change

Global **climate change** is also a consequence of human population needs for energy, and the use of fossil fuels to meet those needs. Essentially, burning **fossil fuels**, including as oil, natural gas, and coal, increases carbon dioxide concentrations in the atmosphere. Carbon dioxide traps heat energy from the sun, resulting not only in an average increase in global temperature but also in changing precipitation patterns and increased frequency and severity of extreme weather events, such as hurricanes. Scientists overwhelmingly agree the present warming trend is caused by humans. See the Climate Change chapter for a detailed description its cause and impacts. A few examples of how climate change impacts biodiversity are described in the paragraphs below.

Climate change is recognized as a major extinction threat, particularly when combined with other threats such as habitat loss. Scientists disagree about the likely magnitude of the effects, with extinction rate estimates ranging from 15 percent to 40 percent of species committed to extinction by 2050. By altering regional climates, it makes habitats less hospitable to the species living in them. The warming trend will shift colder climates toward the north and south poles, forcing species to move (if possible) with their adapted climate norms. For example, one study indicates that European bird species ranges have moved 91 kilometers (56.5 miles) northward, on average. The same study suggested that the optimal shift based on warming trends was double that distance, suggesting that the populations are not moving quickly enough. Range shifts have also been observed in plants, butterflies, other insects, freshwater fishes, reptiles, amphibians, and mammals.

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 (figure $10.7.a$). 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.

Figure $10.7.a$: Historically, grizzly bear habitat extended from Mexico through the western United States and into the mid-latitudes of Canada. Since 2008, grizzly bears (*Ursus arctos horribilis*) have been spotted farther north than their historic range, a possible consequence of climate change. Their range now extends to the northern tip of Canada and throughout Alaska. As a result, grizzly bear habitat now overlaps polar bear (*Ursus maritimus*) habitat. The two kinds of bears, which are capable of mating and producing viable offspring, are considered separate species as historically they lived in different habitats and never met. However, in 2006 a hunter shot a wild grizzly-polar bear hybrid known as a grolar bear, the first wild hybrid ever found.

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

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. For example, pollinating insects typically emerge in the spring based on temperature cues. In contrast, many plant species flower based on daylength cues. With warmer temperatures occurring earlier in the year, but daylength remaining the same, pollinators ahead of peak flowering. As a result, there is less food (nectar and pollen) available for the insects and less opportunity for plants to have their pollen dispersed. For migrating birds, timing is everything – they must arrive at their summer breeding grounds when food supplies are at their peak, so that they can rebuild their body fat and reproduce successfully. In some areas, birds are showing up early, before flowers open or insects hatch, and finding very little to eat.

Ocean levels rise in response to climate change 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 freshwater.

Finally, increased carbon dioxide levels in the atmosphere react with ocean water to form carbonic acid, a phenomenon called **ocean acidification**. In combination with warmer temperatures, ocean acidification is responsible for coral bleaching, the process by which coral expel the algae that typically conduct photosynthesis within the corals. Ocean acidification can also dissolve the calcium carbonate skeletons formed by the coral. Overall, climate change plays a major role in the loss of nearly one third of coral reefs.

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10.8: Data Dive- Threats to Biodiversity

Overview

Starting in 1998, the World Wildlife Federation (WWF) began publishing the Living Planet Report. This report analyzes the health of the plant relative to the impact humanity has on it, and is updated every two years. This report continually urges humanity, especially world leaders, to work together to build a more sustainable, resilient, and healthy future for people and nature. In the 2018 update, there was an overview of the major threats to biodiversity for several animal families of concern. See the graph of their results below:

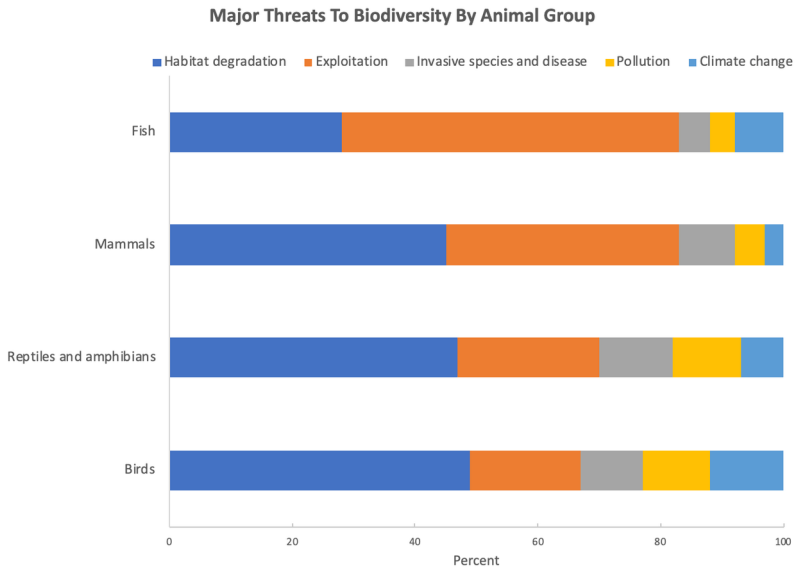

Figure $10.8.a$: Percent of biodiversity threats to various animal groups. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Living Planet Report 2018 Aiming Higher.

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What animal category above is most affected by habitat destruction? What about exploitation?
3. What category above has the largest impact (on average) on all species?
4. What is different for the fish data patterns compared to the other animal categories? Why?
5. How can the results of this graph to inform future conservation efforts?
6. Based on what you have learned in the chapter, list two other categories of life that you think should be added to the graph. Provide at least one reason for each as to why you think it should be added.

Raw Data From Above Graph(s)

Table $10.8.a$**:** Raw data for percent of biodiversity threats to various animal groups. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Living Planet Report 2018 Aiming Higher.

Animal Group	Habitat Degradation	Exploitation	Invasive Species And Disease	Pollution	Climate Change
Birds	49	18	10	11	12
Reptiles/Amphibians	47	23	12	11	7
Mammals	45	38	9	5	3

Animal Group	Habitat Degradation	Exploitation	Invasive Species And Disease	Pollution	Climate Change
Fish	28	55	5	4	8

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10.9: Review

Summary

After completing this chapter you should be able to...

- Describe biodiversity as the equilibrium of naturally fluctuating rates of extinction and speciation.
- Summarize potential causes of mass extinctions and the associated biodiversity loss.
- Compare the present rate of extinction to the background extinction rate.
- Describe the causes and consequences of the sixth mass extinction.
- Describe how the loss of biodiversity is measured.
- Distinguish among the Red List categories.
- Name, define, and provide examples of the five major threats to biodiversity.
- Provide examples of the successes and failures of biological control in regulating invasive species.

Five mass extinctions with losses of more than 50 percent of extant species are observable in the fossil record. The **sixth mass extinction** is currently in progress with present-day extinction rates much greater than the **background extinction rate**.

The core threats to biodiversity are human population growth and unsustainable resource use. These are habitat loss, overexploitation, pollution, invasive species, and climate change. **Habitat loss** occurs through deforestation, damming of rivers, and other activities. Water and air **pollution** introduce toxic substances into the environment that harm plants and animals. **Overexploitation** is a threat particularly to aquatic species, but the poaching of terrestrial animals and overcollection of plants and fungi also puts species at risk. **Invasive species** have been the cause of a number of extinctions and are especially damaging to islands and lakes. **Climate change** is forcing range changes that can lead to extinction. It is also affecting adaptations to the timing of resource availability that negatively affects species in seasonal environments. Climate change will also raise sea levels, eliminating some islands and reducing the area of all others.

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11: PROTECTING BIODIVERISTY

Chapter Hook

As of 2020, there were 41,415 species on the International Union for Conservation of Nature (IUCN) Red List, 16,306 of them being endangered and threatened with extinction. This is up from 16,118 from 2019. The Island Fox (*Urocyon littoralis*) is only found on six of the California Channel Islands off the coast of southern California. In the mid-1990's four island fox subspecies experienced drastic population declines. Soon after, they were listed as critically endangered on the IUCN red list and endangered on the U.S Endangered Species Act. However, due to uncompromising recovery efforts (through supported funding from its endangered status), all four subspecies have almost completely recovered their populations. Regrettably, not all species that end up on the IUCN red list or endangered species list have trajectories that later hold such hope.

Figure $11.a$ Island fox (*Urocyon littoralis*). Image by USFWS (licensed under CC-BY 2.0)

The field of **conservation** focuses on preserving biodiversity. Effective conservation depends on ecological knowledge. Today, the main efforts to preserve biodiversity involve legislative approaches to regulate human and corporate behavior, setting aside protected areas, and ecosystem restoration.

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11.1: Policies
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11.3: Species-level Conservation
11.4: Protected Areas
11.5: Ecosystem Restoration
11.6: Economic Influences on Conservation
11.7: Individual Choices
11.8: Data Dive- Island Fox Populations
11.9: Review

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11.1: Policies

National and State Laws

Within many countries there are laws that protect endangered species and regulate hunting and fishing. For example, the **Endangered Species Act** (ESA) was enacted in 1973 in the United States. The ESA does not automatically protect species categorized as threatened on the Red List. Instead, the U.S. Fish and Wildlife Service (FWS), which enforces the ESA, assesses candidates for protected status as threatened or endangered (figure $11.1.a$). Consideration of candidate species can be initiated by the FWS itself or at the request of the public. Through the Species Status Assessment Framework, the FWS compiles biological data, such as habitat and population information and current threats to the species. This biological data is used to inform decisions.

Figure $11.1.a$: Public Affairs Specialist for the U.S. Fish and Wildlife Service, Joanna Gilkeson, takes photos of federally endangered San Diego fairy shrimp in a vernal pool in Otay Mesa, California. Vernal pools are shallow seasonal ponds, and vernal pool species are uniquely adapted to changes in water availability. Image by Maideline Sanchez/USFWS (public domain).

Once a species is listed, the FWS is required by law to develop a management plan to protect the species and bring it back to sustainable numbers. The ESA, and others like it in other countries, is a useful tool, but it suffers because it is often difficult to get a species listed or to get an effective management plan in place once a species is listed.

The 1972 **Marine Mammals Protection Act** prohibits the “take” of marine mammals—including harassment, hunting, capturing, collecting, or killing—in U.S. waters and by U.S. citizens on the high seas. The act also makes it illegal to import marine mammals and marine mammal products into the United States without a permit.

State laws can also aid in conservation. Through **California Endangered Species Act** (CESA), originally passed in 1970 and subsequently amended, the California Fish and Game Commission assesses species to be listed as threatened or endangered by the state. A listed species, or any part or product of the plant or animal, may not be imported into the state, exported out of the state, “taken” (killed), possessed, purchased, or sold without proper authorization.

Note that endangered is a subcategory of threatened on the Red List, but for ESA and CESA, threatened and endangered are separate categories, with the latter representing at the greater risk of extinction.

International Agreements

The **Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)** treaty came into force in

1975. The treaty, and the national legislation that supports it, provides a legal framework for preventing listed species from being transported across nations' borders, thus protecting them from being caught or killed when the purpose involves international trade.

Species can be listed in one of three CITES appendices. Trade is banned for Appendix I species, which are threatened with extinction. For example the trade of ivory is banned by CITES. Trade is regulated for Appendix II species, such as the meat and shells of the queen conch or big-leaf mahogany (figure $11.1.b$). Appendix III species are protected in at least one country, and the local government needs a coordinated response through CITES. For example, several species of red and pink corals have been added to Appendix III at the request of China.

Figure $11.1.b$: Big-leaf mahogany (*Swietenia macrophylla*) timber is used to make furniture, musical instruments, boats, and other products. It listed in CITES Appendix II, meaning that it is regulated. Specifically, a permit is required to ship big-leaf mahogany timber. Image by Forest and Kim Starr (CC-BY).

Approximately 35,800 species are protected by the CITES. 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 **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.

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11.2: Non-profit Organizations

The private non-profit sector plays a large role in the conservation effort both in North America and around the world. For example, the World Wildlife Fund raised over $300 million in the 2017-2018 fiscal year to protect endangered animals, their habitats, and natural resources. Some non-profit organizations are species specific, like the Orangutan Foundation, and others are broadly focused, such as the IUCN and Trade Records Analysis of Flora and Fauna in Commerce (TRAFFIC). Illegal wildlife trade is monitored by TRAFFIC. The Nature Conservancy (figure $11.2.a$) takes a novel approach. It purchases land and protects it in an attempt to set up preserves for ecosystems.

Figure $11.2.a$: Jo-Ellen Darcy (left), Assistant Secretary of the Army for Civil Works, discusses the Hamilton City with Ryan Luster, project director for The Nature Conservancy, during a site tour in Hamilton City, Calif., June 3, 2014. The U.S. Army Corps of Engineers Sacramento District's Hamilton City project will let nature help do the work of reducing flood risk by restoring 1,500 acres of native habitat between the Sacramento River and a new setback levee to be built near the town. The Nature Conservancy assisted the project partners by helping acquire the land planned for restoration. Image by US Army Corps of Engineers (public domain).

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11.3: Species-level Conservation

Some conservation efforts center around a single species. Often this is a charismatic species that elicits public interest, such as tigers, sea otters, or the California Condor. The specific approach depends on the specific threats to the focus species. When California Condor population size plummeted, leaving only 23 individuals, they were relocated into a controlled environment and provided with optimal conditions for reproduction. This is called **captive breeding**. Individuals have since been **reintroduced** into the environment. One threat to the species was lead from bullets that were entering the food chain and ultimately poisoning the California Condor. Public education and providing lead-free bullets was thus another component of their conservation plan. By 2016, the population size increased to 446 individuals, with 276 of those living in the wild.

When disease puts species at risk, vaccination may be part of the conservation plan. For example, the black-footed ferret of the Great Plains is threatened by sylvatic plague as well as habitat loss. In response, peanut buttered-flavored oral vaccines were distributed over their habitats. Conservation efforts also focused on captive breeding and reintroduction. Once thought to be extinct, there are now several hundred black-footed ferrets in captivity and similar numbers in the wild (figure $11.3.a$).

Figure $11.3.a$: A black-footed ferret kit at the National Black-footed Ferret Conservation Center in Colorado. Image by Ryan Moehring/USFWS (CC-BY)

Protecting or restoring habitat is another component of species-level conservation. For example, the Northern Spotted Owl lives in old-growth forests. Protecting intact old-growth forests and restoring forest habitat is thus critical to their success. This is accompanied by removal of the Barred Owl, an invasive that competes with the Northern Spotted Owl. Similarly, removal of the invasive iceplant *Carpobrotus edulis* from California coasts, restores conditions for endangered dune vegetation (figure $11.3.b$-d). In other cases, habitat restoration involves promoting populations of native species that support those at risk, such as promoting vegetation that provides food and shelter for waterfowl.

Figure $11.3.b$: Vegetation at Martin Dunes in California. Iceplant is visible in the forefront. Photo by USFWS (public domain).

Figure $11.3.c$: *Carpobrotus edulis* is an invasive iceplant that forms thick mats and outcompetes coastal vegetation. Image by Dr. Dwayne Meadows, NOAA/NMFS/OPR (public domain).

Figure 11.3.d: Removal of the iceplant restores habitat for endangered species, such as Menzies' wallflower. Image by Gordon Leppig & Andrea J. Pickart, FWS (public domain).

Seemingly unimpressive species can still serve vital ecological roles. For example, the delta smelt is an important food source for larger fish species. Additionally, it serves as an **indicator species** because the health of its populations reflect overall ecosystem health. While the delta smelt has been a focus of species-level conservation, non-charismatic species are often overlooked. In fact, a 2007 study by Colléony and colleagues found that people more often donated to conservation efforts for species that were more similar to humans rather than choosing those that were at greatest risk of extinction. Broad approaches such as establishing protected areas and ecosystem restoration benefit charismatic and non-charismatic species alike. Additionally, broad approaches protect unidentified and species that have not been assessed.

References

Colleony, Agathe, Susan Clayton, Denis Couvet, Michel Saint Jalme, and Anne-Caroline Prevot. (2017). Human preferences for species conservation: Animal charisma trumps endangered status. *Biological Conservation*. 206. 263-269. DOI

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11.4: Protected Areas

It is important to protect natural areas for several reasons. Some people feel a cultural or spiritual connection to the wilderness. Every year, millions of people visit recreational lands such as parks and wilderness areas to experience attractions of the great outdoors: hiking among the giant sequoias in California, traveling on a photo safari in Kenya or just picnicking at a local county park. Besides providing people with obvious health benefits and aesthetic pleasures, recreational lands also generate considerable tourist money for government and local economies. Outdoor recreation activities such as hiking and camping benefit tourist industries and manufacturers of outdoor clothes and equipment.

Establishment of preserves is one of the key tools in conservation efforts. A **preserve** is an area of land set aside with varying degrees of protection for the organisms that exist within the boundaries of the preserve (figure $11.4.a$). Governments or private organizations establish nature preserves. In 2016, the IUCN estimated that 14.7 percent of Earth's land surface was covered by preserves of various kinds. This area is large, but only 20% of the key biodiversity areas identified by the IUCN were sufficiently protected.

Figure $11.4.a$: Mequon Nature Preserve in Wisconsin. Image by Jennifer Tomaloff (CC-BY-NC-SA).

There has been extensive research into optimal preserve designs for maintaining biodiversity. Preserves can be seen as "islands" of habitat within "an ocean" of non-habitat. In general, large preserves are better because they support more species, including species with large home ranges; they have more core area of optimal habitat for individual species; they have more niches to support more species; and they attract more species because they can be found and reached more easily. One large preserve is better than the same area of several smaller preserves because there is more core habitat unaffected by less hospitable ecosystems outside the preserve boundary. For this same reason, preserves in the shape of a square or circle will be better than a preserve with many thin "arms." If preserves must be smaller, then providing wildlife corridors between two preserves is important so that species and their genes can move between them. All of these factors are taken into consideration when planning the nature of a preserve before the land is set aside. In addition to the physical specifications of a preserve, there are a variety of regulations related to the use of a preserve. These can include anything from timber extraction, mineral extraction, regulated hunting, human habitation, and nondestructive human recreation.

The public lands described below differ in their level of protection. For example, national parks and forests allow camping whereas wildlife refuges place more limitations on human activities.

Wilderness Areas

Wilderness areas, comprise ecosystems in which human activity has not significantly affected the plant and animal populations or their environment. Natural processes predominate. According to the "Wilderness Act of 1964," wilderness areas are defined

as being those areas where the nearest road is at least five miles away and where no permanent buildings stand. Activities that could disrupt native species, such as the use of motorized vehicles is prohibited. More than 100 million acres of land are now preserved as wilderness under this act. Sparsely populated Alaska contains the largest chunk of wilderness areas, over half of it. Although wilderness areas are scattered among most of the lower 48 states, the largest percentage is found in the western states. Few undesignated areas in the contiguous states remain that would qualify as wilderness.

National parks and forests and wildlife refuges can contain wilderness areas. California contains significant wilderness areas, with over 4 million acres of National Forest Wilderness areas, and 1.5 million acres of mostly desert wilderness in the Mojave Desert National Preserve (figure $11.4.b$).

Figure $11.4.b$: A variety of unique plant life grows at Mojave Desert National Preserve. Image by John Fowler (CC-BY).

Wilderness areas provide an essential habitat for a wide array of fish, wildlife, and plants, and are particularly important in protecting endangered species. For scientists, wilderness areas serve as natural laboratories, where studies can be performed that would not be possible in developed areas.

National and State Parks

The United States has set aside more land for public recreational use than any other country. The **National Park System** manages more than 380 parks, recreation areas, seashores, trails, monuments, memorials, battlefields, and other historic sites. It consists of more than 80 million acres nationwide (figure $11.4.c$). The largest national park is Wrangell–St. Elias National Park and Preserve in Alaska with over 13 million acres. California has eight national parks: Channel Islands, Death Valley, Joshua Tree, Lassen, Redwood, Sequoia, Kings Canyon, and Yosemite. Many national parks such as Yosemite, Yellowstone and the Grand Canyon are such popular recreation destinations that the ecosystems of those parks are being severely tested by human activities.

Figure 11.4.c: National parks, such as Grand Teton National Park in Wyoming, help conserve biodiversity. (credit: Don DeBold)

Every state has also set aside significant amounts of land for recreational use. The **California State Park System** manages more than one million acres of parklands including: coastal wetlands, estuaries, scenic coastlines, lakes, mountains and desert areas. California's largest state park is Anza-Borrego Desert State Park, which is the largest state park in the United States with 600,000 acres. The stated mission of the California State Park System is "to provide for the health, inspiration and education of the people of California by helping to preserve the state's extraordinary biological diversity, protecting its most valued natural and cultural resources and creating opportunities for high-quality outdoor recreation".

National Forests

The **National Forest System**, managed by the U.S. Forest Service (part of the United States Department of Agriculture), consists of more than 170 forestlands and grasslands, which are available for activities such as camping, fishing, hiking and hunting. These are managed as multiple use lands, which balance the needs for recreation, grazing, timber, watershed protection, wildlife and fish, and wilderness.

Some examples of national forests are the Sierra National Forest in California and the White Mountain National Forest in New Hampshire. The Coronado National Forest in Arizona is famous for "sky islands", or steep mountain ranges surrounded by low-lying areas. The dramatic increase in elevation is associated with changes in the flora and fauna (figure 11.4.d). Explore national forests using this interactive map.

Figure $11.4.d$: The Santa Teresa Mountains of the Coronado National Forest form "sky islands". Image by Jstuby (public domain).

Wildlife Refuges

The U.S. Fish and Wildlife Service manage more than 500 national **wildlife refuges** (figure $11.4.e$), which not only protect animal habitats and breeding areas but also provide recreational facilities. Find a Refuge is an interactive map for locating wildlife refuges.

Figure $11.4.e$: Bobcat at Sonny Bono National Wildlife Refuge in southern California. Image by Mark Stewart/USFWS (public domain).

Supplemental Reading

America's Public Lands Explained. 2016. U.S. Department of the Interior.

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- Multiple Use Lands. 12 May 2015. The United States Department of Justice. Accessed 28 March 2021 (public domain)

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11.5: Ecosystem Restoration

Ecosystem restoration is the process of bringing an area back to its natural state, before it was impacted through destructive human activities. It holds considerable promise as a mechanism for maintaining or restoring biodiversity and reinstating ecosystem services. It requires a broad interdisciplinary approach involving many different scientific fields of study (for example, biology, ecology, hydrology and geology). Reintroducing wolves, a top predator, to Yellowstone National Park in 1995 led to dramatic changes in the ecosystem that increased biodiversity. The wolves (figure $11.5.a$) function to suppress elk and coyote populations and provide more abundant resources to the detritivores. Reducing elk populations has allowed revegetation of **riparian areas** (those along the banks of a stream or river), which has increased the diversity of species in that ecosystem. Reduction of coyote populations by wolves has increased the prey species previously suppressed by coyotes. In this ecosystem, 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.

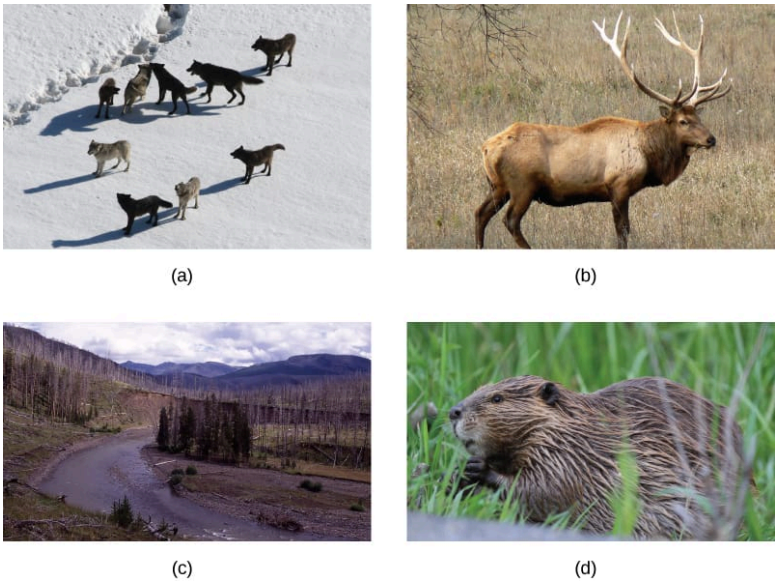

Figure $11.5.a$: (a) The Gibbon wolf pack in Yellowstone National Park, March 1, 2007, represents a keystone species. The reintroduction of wolves into Yellowstone National Park in 1995 led to a change in the grazing behavior of (b) elk. To avoid predation, the elk no longer grazed exposed stream and riverbeds, such as (c) the Lamar Riverbed in Yellowstone. This allowed willow and cottonwood seedlings to grow. The seedlings decreased erosion and provided shading to the creek, which improved fish habitat. A new colony of (d) beaver may also have benefited from the habitat change. (credit a: modification of work by Doug Smith, NPS; credit c: modification of work by Jim Peaco, NPS; credit d: modification of work by “Shiny Things”/Flickr)

Other large-scale restoration experiments underway involve dam removal. 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 (see Dams and Reservoirs for more about the impact of dams). In the Pacific Northwest of the United States, dam removal projects are expected to increase populations of salmon, which is considered a keystone species because it transports nutrients to inland ecosystems during its annual spawning migrations. In other regions, such as the Atlantic coast, dam removal has allowed the return of other spawning anadromous fish species (species that are born in fresh water, live most of their lives in salt water, and return to fresh water to spawn). Some of the largest dam removal projects have occurred recently, such as Elwha Dam on the Olympic Peninsula of Washington State. The large-scale ecological experiments that these removal projects constitute will provide valuable data for other dam projects slated either for removal or construction.

Besides physical processes, socioeconomic factors must also be considered in a restoration project. Actions of humans have historically been important in shaping ecosystems, and are important in determining the success of restoration efforts. Because

the cost to restore an individual site can involve millions of dollars, government support is a necessity.

Environmental Remediation

Danger to human health from both historic and modern pollution requires that cleanup measures be implemented. **Remediation** is aimed at neutralization, containment, and/or removal of the polluting chemicals. The goal is to prevent the spread of the pollution, or to reduce it to levels that will not appreciably risk human health. Many times, it is physically impossible or financially unfeasible to completely clear all contamination. Often, experts and the public disagree on how clean is clean enough.

Many communities are struggling to find the funds and technological expertise needed to clean up polluted areas. Some settings, such as brownfields, can be remediated fairly easily. **Brownfields** are abandoned industrial or commercial facilities or blighted urban areas that need to be cleansed of contamination before they can be redeveloped. Other areas, because of their size or the extreme toxicity of their contaminants, require very expensive, complex, and long-term remediation. Many of these have been designated as Superfund sites.

Superfund sites are areas with the most toxic contamination in the United States. The contamination may not only make the site itself too dangerous to inhabit, but often leaks toxic levels of pollutants into the surrounding soil, water, or air. An example of a Superfund site is Love Canal in Niagara Falls, New York (figure $11.5.b$). The canal was a chemical waste dump for many years, then in the 1950's was covered with soil and sold to the city. Over time, many homes and a school were built over the former dump. In the 1970's, heavy rains raised the water table and carried contaminants back to the surface. Residents noticed foul smells, and gardens and trees turned black and died. Soon after, rates of birth defects, cancer, and other illnesses began to rise sharply. In 1977, the State of New York and the federal government began remediation work. Buildings were removed, and all residents were bought out and relocated, contaminated deposits and soils were excavated, and remaining soils and groundwater were treated and sealed off to prevent further spread of the contamination. Remediation activities have now been completed at this site.

Figure $11.5.b$: Love Canal. Source: US Environmental Protection Agency

The type of pollution and the medium affected (air, water, or soil) determine remediation methods. Methods include incineration, absorption onto carbon, chemical methods, or bioremediation. **Bioremediation** is the use of plants, bacteria, or fungus to "digest" the contaminant to a non-toxic or less toxic form. All of these methods tend to be expensive and time-consuming.

Reclamation and Mitigation

Reclamation involves salvaging some features of a degraded habitat, but it may not restore the ecosystem fully (figure $11.5.c$). For example, instead of abandoning a mined area once resources have been collected, it can be reclaimed by planting vegetation, reshaping the landscape, and redirecting water flow. However the reclaimed land still lacks many features of the original ecosystem, such as complex topography, vegetation that took tens or hundreds of years to grow, soil quality, and an intricate network of streams.

Figure 11.5.c: The Seneca Yoast coal once land has been cleared in preparation for mining (left) and after reclamation (right). Image by Peabody Energy, Inc. (CC-BY).

Sometimes, actions can be taken to avoid, reduce or compensate for the effects of environmental damage. Such **mitigation** efforts have been taken by the Army Corps of Engineers during construction projects. The native plants are removed from a site before construction begins and transplanted at a special holding site. After the construction project is completed, the native plants are replanted using those from the holding site. Another example of mitigation might involve the creation or enhancement of wetlands in one area, in order to compensate for permitted wetland losses in another area. Mitigation often goes hand-in-hand with restoration. Texaco, in conjunction with environmental groups and the United States Fish and Wildlife Service, restored 500 acres of agricultural lands in the lower Mississippi Delta to bottomland hardwoods. Texaco received environmental credits for the mitigating effects of the new woodlands on air quality.

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11.6: Economic Influences on Conservation

Economics greatly impacts conservation success. Short-term profits can incentivize individuals, companies, or governments to harvesting resources at an unsustainable rate and at the expense of ecosystem health. In impoverished regions, compromising habitat to grow high-value crops, such as coffee or oil palms, or poaching endangered species may seem like the only source of income. One solution is **debt-for-nature swaps** through which one country forgives the debt of another if the latter agrees to protect natural areas. These conservation efforts can provide a new source of income for residents near the protected areas. For example, the United States forgave $20 million in debt from Costa Rica. In exchange, Costa Rica invested in expanding its protected areas and developing the ecotourism industry, which provides jobs to many of its residents (figure $11.6.a$). **Ecotourism** involves visiting and enjoying natural areas while minimizing ecological damage. Ecotourism can benefit local economies and alleviate poverty especially if the earnings from it are reinvested into the communities living near tourist destinations. It generates jobs such as park operators, sellers of local crafts, and tour guides.

Figure $11.6.a$: A tourist ziplines over the Costa Rican rainforest. Image by Khaufle at the English language Wikipedia (CC-BY-SA).

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11.7: Individual Choices

Many of the strategies for preserving biodiversity operate at the level of whole governments or large organizations; however, your choices as an individual also play a role in conservation.

Consumer Choices

The products you purchase have differing impacts on biodiversity. Educating yourself on the origin of products and food that you purchase and choosing the sustainable options can help preserve biodiveristy. For example, arabica coffee can be grown in the shade, meaning there is no need to fully clear rainforest vegetation when growing this species (figure $11.7.a$). However, robusta coffee requires full sun, and cultivating it has a greater impact or rainforest biodiversity. Monterey Bay Aquarium provides a sustainable seafood guide, which identifies seafood choices that have a lower environmental impact. Choosing local products reduces the amount of fossil fuels that were burned to transport them to you, thus reducing carbon emissions that contribute to climate change.

Figure $11.7.a$: Shade-grown coffee at a Columbian farm. Image by Brian Smith/American Bird Conservancy/U.S. Fish and Wildlife Service Northeast Region (CC-BY).

Some products have special certifications that indicate their impact on biodiversity. For example, certified organic products must be cultivated without the use of synthetic pesticides, herbicides, and fertilizers, which pollute the surrounding areas. Additionally, they cannot contain genetically modified organisms (GMOs), which have both positive and negative environmental implications. If you cannot afford to buy all organic produce, see the Environmental Working Group's lists of the Clean Fifteen™ (for which pesticide use is already limited) and Dirty Dozen™ (which are high priority to purchase organic or avoid due to high pesticide residues). The Roundtable on Sustainable Palm Oil (RSPO) certifies oil palm plantations that follow standards such as avoiding deforestation and using fire to clear land. Additionally, RSPO-certified business must follow guidelines to compensate their employees sufficiently. Fair Trade Certified™ goods must meet social and environmental standards that support the United Nation's Sustainable Development Goals.

Resource Conservation

Resource conservation is individual choice that can promote biodiversity. In this case, conservation refers to limiting one's use of resources, such as water, electricity, and gasoline. Landscaping with drought-tolerant plants to limit the need for irrigation or using a low-flow shower head are examples of water conservation. Because much electricity is generated from burning fossil fuels, such as coal and natural gas, conserving electricity reduces carbon emissions associated with climate change. Turning off lights and appliances when not in use and insulating one's home to reduce electricity spent on heating and cooling save money

and benefit the environment. Similarly, transportation choices such as carpooling, biking, or taking public transportation can limit carbon emissions. Reusing items or not purchasing unnecessary ones also conserves the energy needed to produce and transport these goods and reduces plastic waste, which is particularly harmful to aquatic ecosystems. See chapters about Water Resources, Renewable Energy, and Solid Waste Management for more about resource conservation.

Guide to Planting a Pollinator Garden

Whether you have a few feet on your apartment balcony or several acres, you can promote populations of native bees, butterflies, and other pollinators by building a **pollinator garden** (figure $11.7.b$). The first step is to choose a location. While flowering plants can grow in both shady and sunny locations, consider your audience. Butterflies and other pollinators like to bask in the sun and some of their favorite wildflowers grow best in full or partial sun with some protection from the wind. The next step is to identify your soil type. Take a look at your soil - is it sandy and well-drained or more clay-like and wet? You can turn over a test patch or check out a soil mapper to learn more. Your soil type and the amount of sunlight it gets will help determine the kinds of plants you can grow.

Figure $11.7.b$: A diversity of plant species support native pollinators in this pollinator garden. Image by Sara "Asher" Morris (CC-BY-NC).

Next, research which varieties of milkweed and wildflowers are native to your area and do well in your soil and sunlight conditions. **Native plants**, those that have historically occurred in the area, are the ideal choice, because they require less maintenance and tend to be heartier. Find a nursery that specializes in native plants near you - they'll be familiar with plants that are meant to thrive in your region. Some examples of pollinator-friendly plants native to California, include the California poppy, California lilac, milkweed, and foothill penstemon. The California Native Plant Society and UC Berkeley Urban Bee Lab have additional plant suggestions. It's essential to choose plants that have not been treated with pesticides. Choosing **perennials** will ensure your plants come back each year, reducing the need for maintenance.

Remember to think about more than just the summer growing season. Pollinators need nectar early in the spring, throughout the summer and even into the fall. Choosing plants that bloom at different times will help you create a bright and colorful garden that both you and pollinators will love for months!

Some native bee species use bare soil for nesting. While applying mulch can help control weeds, leaves some bare soil if possible. Some native pollinators also nest in tiny cavities, which may already occur naturally in or near your garden or can be provided with bee boxes.

Make sure to weed and water your garden to keep it healthy. It may take some time, but you will eventually see butterflies and other pollinators enjoying your garden.

Modified by Melissa Ha from the U.S. Fish and Wildlife Service (public domain).

Citizen Science

Finally, citizen science provides the opportunity to be directly involved in biological conservation efforts. For some opportunities like Globe at Night, which assess light pollution, or the Lost Ladybug Project, data can be collected independently and submitted online. Others, like bird banding, are scheduled events in which experts train a group of volunteers to complete fieldwork (figure $11.7.c$). The federal government's citizen science database lists many such opportunities.

Figure $11.7.c$: Left: Students returning from taking phenology measurements on native trees in a native forest conservation area on Hawaii Island. Phenology refers to the timing of events in an organism's life cycle. Right: Americorp members preparing ʻōhiʻa tree cuttings for rooting and propagation – with plants to be used for disease resistance screening. Left image by UFS/USDA (public domain). Right image by USFS (public domain).

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11.8: Data Dive- Island Fox Populations

Overview

The Island Fox Conservation Working Group and Friends of the Island Fox nonprofit organization work hard to continually fund research and conservation projects to ensure the continued survival of the island fox. In addition, they also have educational outreach programs about the island fox as an endangered species to get public support. Every June the Island Fox Conservation Working Group meets to go over updates and plan for the future. In the 2019 meeting they discussed population trends across the six island fox subspecies and determine what those populations mean for the subspecies trajectory moving into the future. The results of this meeting can be seen in the graph and table below:

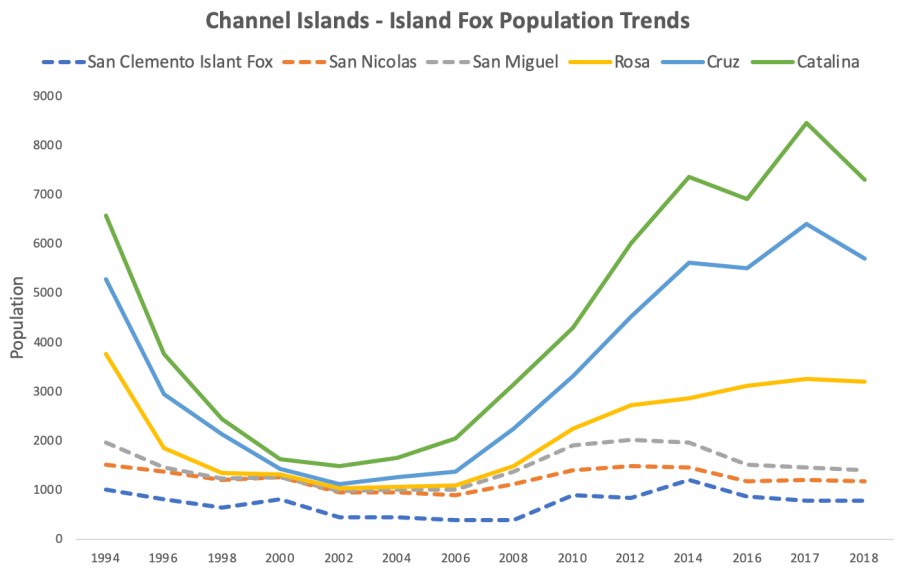

Figure $11.8.a$: Population trends for subspecies of island fox (solid lines = large island subspecies, dashed lines = small island subspecies). Graph by Rachel Schleiger (CC-BY-NC) modified from data in 2019 Island Fox Status Update.

Table $11.8.a$**:** The 2019 designated statuses for the subspecies of island fox based on fox population and island size. Graph by Rachel Schleiger (CC-BY-NC) modified from data in 2019 Island Fox Status Update.

Island	Island Size	Fox Population	Status
San Miguel	Small	171	Concerned
San Nicolas	Small	400	Improved
Santa Rosa	Large	1862	Stable
Santa Cruz	Large	2462	Stable
Santa Catalina	Large	1571	Stable
San Clemento	Small	778	Stable

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph and table?
3. Which subspecies of island fox do you think is the most stable? Why?
4. Which year(s) were bad (meaning population estimates were very low) for most of the island fox subspecies?

5. As noted in the graph, populations are estimated for each subspecies annually. Why do you think an annual estimation was chosen in the conservation plan instead of a longer time interval?

Raw Data From Above Graph(s)

Table $11.8.b$**:** Raw data for population trends for subspecies of island fox (solid lines = large island subspecies, dashed lines = small island subspecies). Graph by Rachel Schleiger (CC-BY-NC) modified from data in 2019 Island Fox Status Update.

Year	San Clemento	San Nicolas	San Miguel	Santa Rosa	Santa Cruz	Santa Catalina
1994	1000	520	450	1800	1500	1300
1996	810	550	100	400	1100	800
1998	650	550	40	100	800	300
2000	800	450	20	50	100	200
2002	450	500	25	60	90	350
2004	450	500	50	70	200	375
2006	400	506	100	80	300	650
2008	400	725	260	100	750	900
2010	900	500	500	350	1050	1000
2012	850	640	525	700	1800	1500
2014	1200	263	510	900	2750	1750
2016	860	329	329	1600	2400	1400
2017	775	255	255	1800	3150	2050
2018	790	400	200	1800	2500	1600

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11.9: Review

Summary

After completing this chapter you should be able to...

- Describe the legislative framework for conservation, providing and describing examples of national and state laws and international agreements.
- Summarize the role of non-profit organizations in conservation.
- Discuss species-level conservation in terms of its success and shortcomings.
- Provide specific examples of species-level conservation, including the name of the species and the strategies used.
- Explain the importance of protected areas and distinguish between different types of protected areas.
- Describe principles of preserve design.
- Identify examples of the effects of ecosystem restoration, remediation, reclamation, and mitigation.
- Explain how economic factors influence conservation efforts.
- Identify actions that individuals can take to preserve biodiversity.

There is a legislative framework for biodiversity protection. In the United States, the **Endangered Species Act** protects listed species but is hampered by procedural difficulties and a focus on individual species. International treaties such as **CITES** regulate the transportation of endangered species across international borders. The non-profit sector is also very active in funding and organizing conservation efforts.

Conservation involves a variety of approaches, and many factors influence the success of conservation efforts. **Species-level conservation** may include **captive breeding and reintroduction**, vaccinations, and habitat restoration. Presently, 14.7 percent of Earth's land surface is protected in some way. **Preserves** are a major tool in conservation efforts, and large, interconnected preserves favor biodiversity. The U.S. government maintains wilderness areas, national and state parks, national forests, and wildlife refuges, which differ in their levels of protection. **Ecosystem restoration** promotes biodiversity, improves conditions for native species, and reinstates ecosystem services. **Debt-for-nature swaps** and **ecotourism** assist conservation efforts economically. Through choosing products that minimize environmental harm and resource conservation, individuals play an important role in preserving biodiversity.

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UNIT 4: HUMANS AND THE ENVIRONMENT

The objective for this unit is to set the stage for understanding how humans have altered the trajectory of Earths abiotic and biotic systems. Specifically this unit will dive into the history of humans on this Earth, how we became successful, how we utilize/ acquire basic necessities (water, food), and the how increasing population densities have influenced environmental health. This unit will also addresses the past and present of how the above variables changed as our population changed.

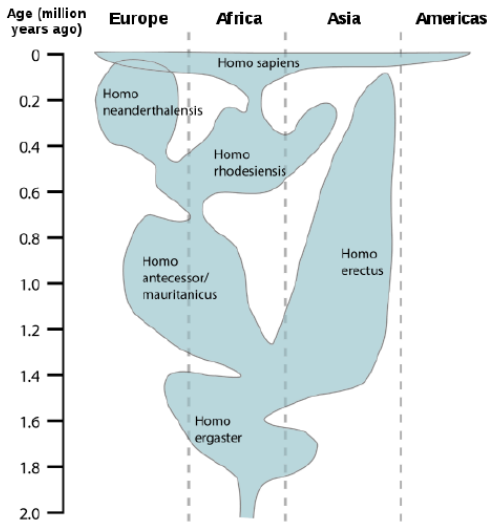

Figure 4.1**:** Chart of human evolution compared to other extinct species of the *Homo* genus. Image by Reed DL, Smith VS, Hammond SL, Rogers AR (licensed under CC-BY 2.5)

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Thumbnail image - "Human ecological footprint" is in the Public Domain

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12: THE HUMAN POPULATION

Chapter Hook

Why is the human species (*Homo sapiens*) so successful? We have the unique ability to not just occupy, but thrive, in diverse environments, even some of the most extreme. Through our social cooperation (despite large groups with no kin), language, art, and ingenuity (especially with tools and fire), our species became unstoppable. Modern humans have permanent settlements on all but one continent (Antarctica) and have exponentially increased our population. We have changed the world! However, this transformation has consequences for all species (including our own), necessitating updated survival strategies across the board.

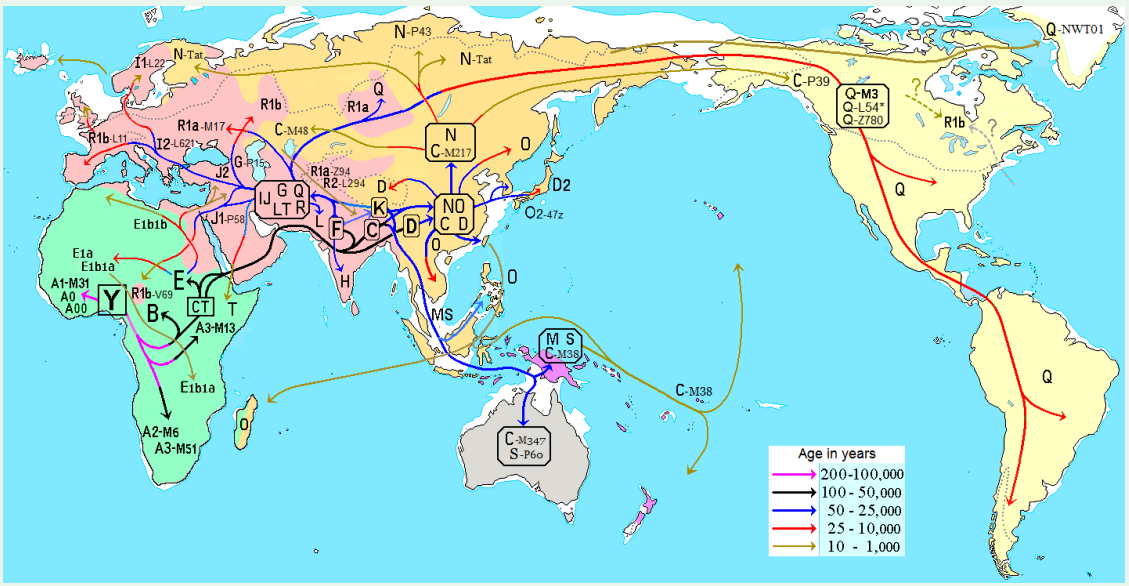

Figure $12.a$ Map demonstrating human spread across the globe. Image by Maulucioni (licensed under CC-BY 3.0)

Concepts of population ecology can be applied to human population growth. **Demography** is the study of how human populations grow, shrink, and change in terms of age and gender compositions. Demographers also compare populations in different countries or regions. The human population has increased dramatically in the last few centuries and continues to grow (figure $12.b$). Overpopulation risks human well-being and compromises ecosystem functioning.

Figure 12.b: The human population continues to grow. China is currently the most populous country with over 1.4 billion people in January of 2022. Image by Sino-German Urbanisation Partnership (public domain).

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12.1: History of Human Population Growth

The human population is growing rapidly. For most of human history, there were fewer than 1 billion people on the planet. During the time of the Agricultural Revolution, 10,000 B.C., there were only 5-10 million people on Earth - which is basically the population of New York City today. In 1800, during the Industrial Revolution, there were approximately 1 billion people on Earth. Continued agricultural expansion and extraction of fossil fuels and minerals led to rapid global economic growth and, in turn, population growth in the 19th century. We've added over 6 billion people to the human population in just a little over 200 years (figure $12.1.a$). As of August 2020, the global human population is around 7.8 billion people.

Although global population size continues to increase, the rate of human population growth has decreased. This means that the population size is not increasing as quickly as it did in the past (figure $12.1.a$).

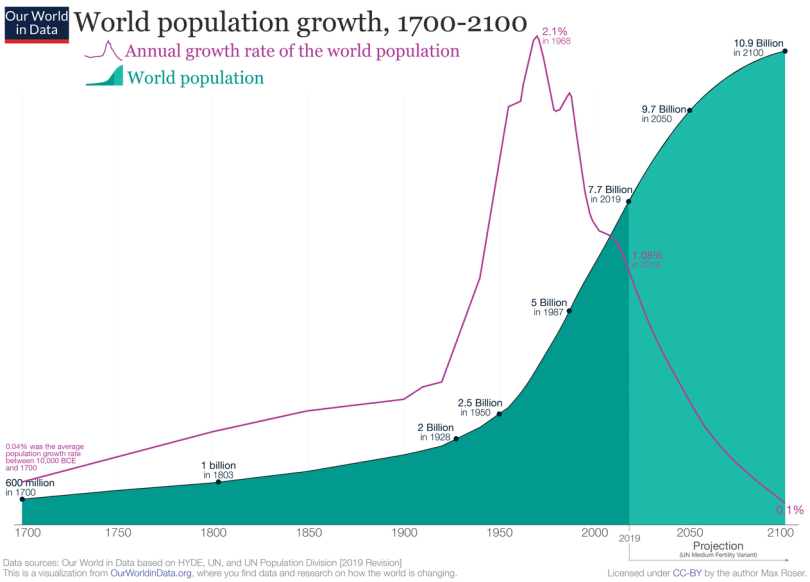

Figure $12.1.a$: Human population growth. Since 1700, human population size (shaded in teal) has increased. It reached 1 billion in 1803, 2 billion in 1928, 2.5 billion in 1950, 5 billion in 1987, and 7.7 billion in 2019. It is projected to reach 10.9 billion in 2100. The population growth rate (pink line) was only 0.04% on average between 10,000 BCE and 1700. The population growth rate peaked in 1968 at 2.1%, and since then, it has slowed to 1.08% in 2019 and is projected to be at 0.1% in 2100. Image by Max Roser (2013) "Future Population Growth". Published online at OurWorldInData.org. (CC-BY)

The fundamental cause of the acceleration of growth rate for humans in the past 200 years has been the reduced death rate due to changes in public health and sanitation. Clean drinking water and proper disposal sewage has drastically improved health in developed nations. Also, medical innovations such as the use of antibiotics and vaccines have decreased the ability of infectious disease to limit human population growth. In the past, diseases such as the bubonic plaque of the fourteenth century killed between 30 and 60 percent of Europe's population and reduced the overall world population by as many as one hundred million people. 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. According to a 2016 study by Marcus et al., The reduction in life expectancy caused by HIV/AIDS was estimated to be 8 years for 2016.

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.

Reference

Marcus, J. L., Chao, C. R., Leyden, W. A., Xu, L., Quesenberry, C. P., Jr, Klein, D. B., Towner, W. J., Horberg, M. A., & Silverberg, M. J. (2016). Narrowing the Gap in Life Expectancy Between HIV-Infected and HIV-Uninfected Individuals With Access to Care. *Journal*

of acquired immune deficiency syndromes (1999), *73*(1), 39–46.

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- The Industrialization of Nature: A Modern History (1500 to the present) from *Sustainability: A Comprehensive Foundation* by Tom Theis and Jonathan Tomkin, Editors. Download for free at CNX. (licensed under CC-BY)

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12.2: The Rate of Human Population Growth

Demographic Transition

Recall from the Populations chapter that the **population growth rate** (*r*) equals the birth rate minus the death rate. Slowly declining birth rates following an earlier sharp decline in death rates are today characteristic of most of the less-developed regions of the world. The shift from high birth and death rates to low birth as well as death rates is called the **demographic transition**.

Prior to World War II, advances in public health were largely limited to affluent, industrialized countries. But since then, many more countries have enjoyed improvements in public health - always with dramatic effect on death rates. For example, in 1945, the death rate in Sri Lanka (then called Ceylon) was 0.022 (2.2%). In 1946, a large-scale program to control mosquitos, which transmit malaria, was started. By eliminating the mosquito, the incidence of malaria dropped sharply. After 9 years, the death rate dropped to 0.010 (1%), and by 2012 was 0.006 (0.6%). However, a compensating decline in birth rates has come more slowly; the birth rate was 0.018 (1.8% in 2012). With birth rates higher than death rates, the population was increasing at an annual rate of 0.012 (1.2%) per year, with a doubling time of 57.5 years (t = 0.69/0.012).

Predicting Future Population Size

Doubling time is based on a constant population growth rate, but this rate can change depending on a number of factors, including total fertility rate (TFR) and the age structure of the population.

Total Fertility Rate

The **total fertility rate** (TFR) is the average number of children that each woman will have during her lifetime. The TFR is an average because, of course, some women will have more, some fewer, and some no children at all. Theoretically, when the TFR = 2, each pair of parents just replaces itself. Actually it takes a TFR of 2.1 or 2.2 to replace each generation - this number is called the **replacement fertility rate -** because some children will die before they grow up to have their own two children. In countries with low life expectancies, the replacement rate is even higher (2.2–3). Figure $12.2.a$ compares the total fertility rate in different countries.

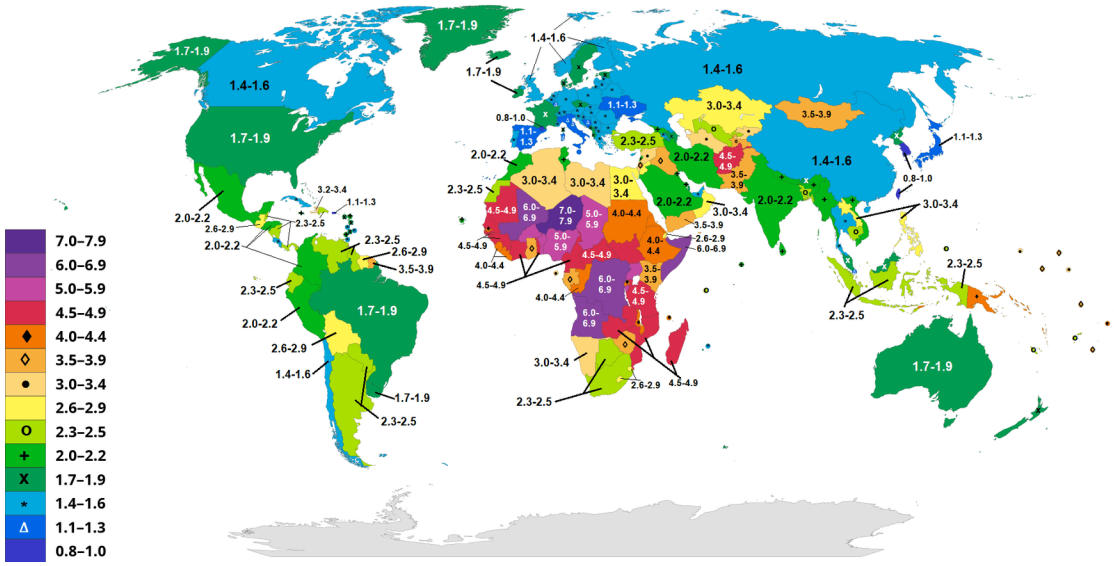

Figure $12.2.a$: Total fertility rate by country in 2020. Most countries in North and South America have a total fertility rate of 1.7-2.5 children per woman, but fertility rates are lower (for example, Canada and Chile) or higher (for example, Guatamala and Bolivia) in a few countries. Most of Europe and northern and Eastern Asia have low fertility rates (generally 1.4-1.6 children per woman). Many Middle Eastern countries and those in southern and southeastern Asia have slightly higher fertility rates (generally 1.7-2.5 children per woman). The fertility rate in Australia is 1.7-1.9 children per woman. High fertility rates are common in African countries. For example, the fertility rate in Niger is 7.0-7.9. Image modified from Korakys (CC-BY-SA).

Age Structure

The **age structure** of a population, the proportion of a population in different age classes, is an important factor in population dynamics. The relationship between TFR and the population growth rate (*r*) depends on age structure. For example, if at one period a population has an unusually large number of children, they will — as they pass through their childbearing years — increase the *r* of the population even if their TFR goes no higher than 2. Most people have children between the ages of 15 and 49. So if a population has a large number of young people just entering their reproductive years, the rate of growth of that population is sure to rise.

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 associated with high birth rates have a pyramidal shape in their age structure diagrams, showing a preponderance of younger individuals, many of whom are of reproductive age (figure $12.2.b$).

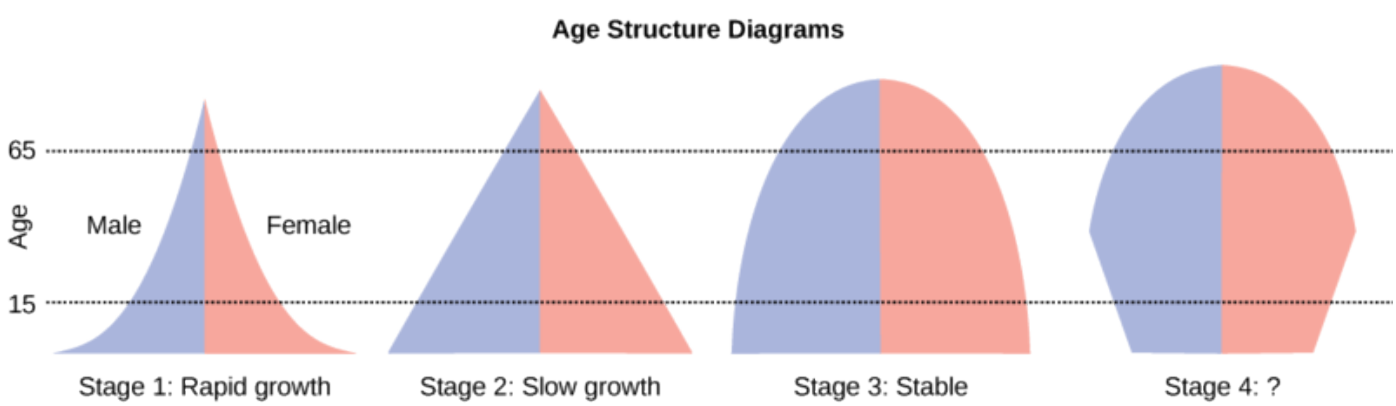

Figure $12.2.b$: Typical age structure diagrams are shown. The rapid growth diagram narrows to a point, indicating that the number of individuals decreases rapidly with age. In the slow growth model, the number of individuals decreases steadily with age. Stable population diagrams are rounded on the top, showing that the number of individuals per age group decreases gradually, and then increases for the older part of the population.

The age structure of a population also reflects the recent pattern of mortality. In countries where injuries, starvation, and disease,

etc. take a heavy toll throughout life, the age structure diagram has a broad base. In countries where almost everyone survives until old age, the bases is narrower.

Rapid growth 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 compared to underdeveloped countries. 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 $12.2.c$, with the highest rates tending to be in the less economically developed countries of Africa and Asia.

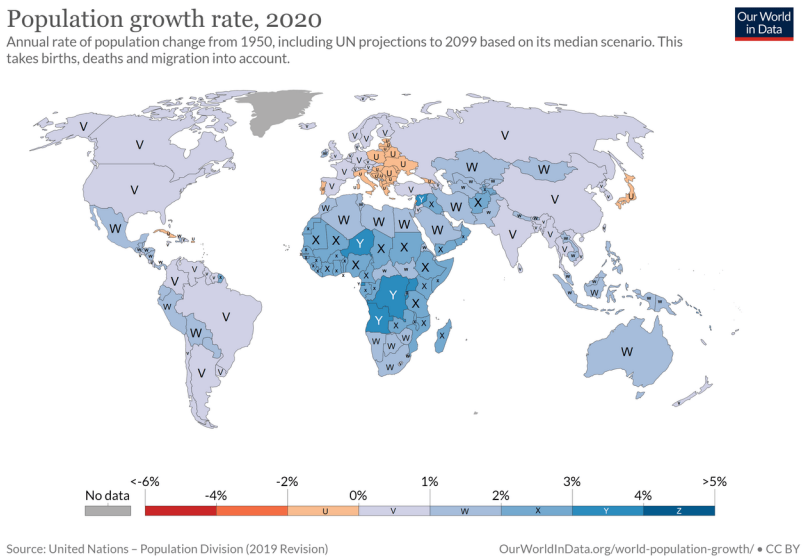

Figure $12.2.c$: The percent growth rate of populations in 2020 in different countries is shown. The population growth rate is negative (meaning the population size is declining) in Cuba, Portugal, many countries in Eastern Europe, and Japan. Mexico, much of Central America, Ecuador, Peru, Bolivia, Paraguay, and Haiti have a population growth rate of 1-2%. Most other countries in North and South America have a population growth rate of 0-1%. Western and Northern Europe and most Asian countries have a population growth rate of 0-1%. In the Middle East, Southeast Asia, Australia, northern and southern Africa, Central African Republic, and South Sudan, the population growth rate is generally 1-2%. Examples of countries with a population growth rate above 2% include the remaining African countries, Syria, Yemen, Oman, Iraq, Afghanistan, and Tajikistan. Image modified from Max Roser, Hannah Ritchie and Esteban Ortiz-Ospina (2013) - "World Population Growth". Published online at OurWorldInData.org (CC-BY).

The U.S. Baby Boom

The TFR in the United States declined from more than 4 late in the nineteenth century to less than replacement in the early 1930s. However, when the small numbers of children born in the depression years reached adulthood, they went on a childbearing spree that produced the baby-boom generation (figure $12.2.d$). In 1957, more children were born in the United States than ever before (or since).

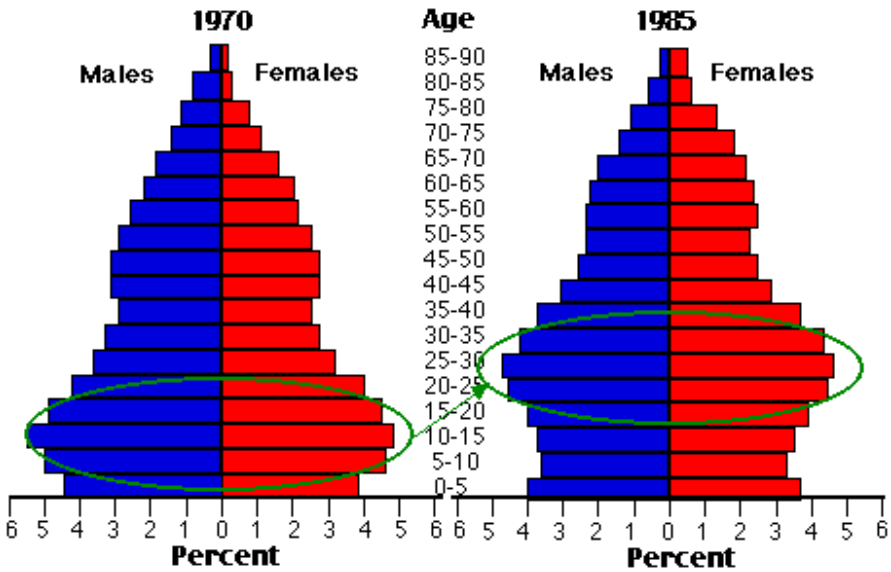

Figure 12.2.d: Age structure diagrams of the United States population in 1970 and 1985. The x-axis represents the percent of the population. The y-axis represents age groups in increments of five from 0-5 years all the way to 85-90 years. Blue bars to the left represent males, and red bars to the right represent females. Bars taper near the top of the diagram, showing that those in the oldest age categories represent a small percentage of the population. The 1970 age structure diagram bulges around the 10-15 age group, and this represents the baby boom (green oval). In 1985, this bulge has moved to the 25-30 age group.

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12.3: Looking Ahead

Population Projections

A consequence of exponential human population growth is that is takes less time to add a particular number of humans to our Earth. Figure $12.3.a$ shows that 123 years were necessary to add 1 billion humans in 1930, but it only took 24 years to add two billion people between 1975 and 1999. As already discussed, at some point it would appear that our ability to increase our carrying capacity indefinitely on a finite world is uncertain. Without new technological advances, the human growth rate has been predicted to continue to slow in the coming decades. However, the population will still be increasing and the threat of overpopulation remains.

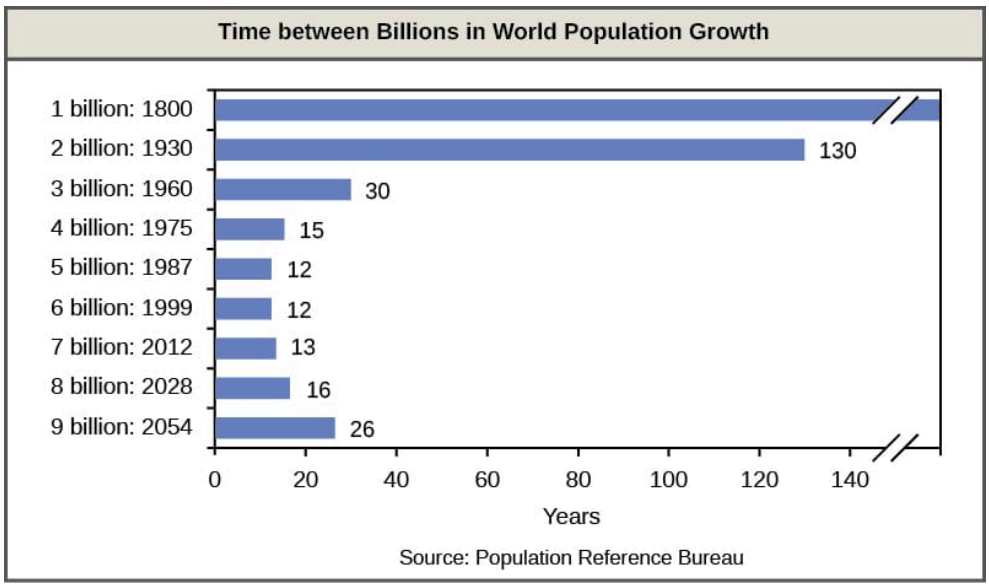

Figure $12.3.a$: The time between the addition of each billion human beings to Earth decreases over time. By 1800, there were about a billion people on Earth. It took 130 years, until 1930, for the number to reach two million. Thirty years later, in 1960, the number reached three billion, and 15 years after that, in 1975, the number reached four billion. The population reached five billion in 1987, and six billion in 1999, each twelve years apart. Currently, the world population exceeds seven billion. The population is projected to reach 8 billion in 2028, and 9 billion in 2054. (credit: modification of work by Ryan T. Cragun)

Exponential growth cannot continue indefinitely. If the current world value for *r* (1.075% in 2019) remains unchanged, the global population would grow from its current 7.8 billion (August 2020) to 9.7 billion by 2050. Experts predict that the global population will continue to grow until 2100, reaching a peak of almost 11 billion. So this begs the question(s)... What is the carrying capacity for humans on Earth? How long until we reach it, or have we already surpassed it? Then finally, what are the consequences of our current and projected populations?

Long-term Consequences

Humans are not unique in their ability to alter their environment. For example, beaver dams alter the stream environment where they are built. Humans, however, have the ability to alter their environment to increase its **carrying capacity**, sometimes to the detriment of other species. Earth's human population and their use of resources are growing rapidly, to the extent that some demographers say that humans have already exceeded our carrying capacity. This would mean that the Earth cannot indefinitely support our current population size. 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.

The impact of humans on our environment depends not only on population size but also on resource use. The **ecological footprint** is a measure of the area of land needed to support an individual or country. This includes agricultural lands used to provide food, other lands used to provide goods (such as forests to provide timber) and fuels (such as oil fields to provide fossil

fuels), and the land needed to dispose of wastes.

Countries differ in the average ecological footprint per person, and these differences are associated with region (figure $12.3.b$). For example, in 2017, the ecological footprint per person in the United States was 8.1 global hectares compared to only 1.2 global hectares in India. (Visit footprintnetwork.org to see ecological footprints and related metrics for all countries.) Many factors affect the size of an ecological footprint from economic development to resource conservation to individual product choice. Reducing our ecological footprints can increase our carrying capacity and decrease environmental impact. So maybe we should update the question of, "What the Earths carrying capacity for humans," to, "What is the carrying capacity of people on Earth at which we can provide a fair and decent life for all humans while causing the minimum impact on the environment?

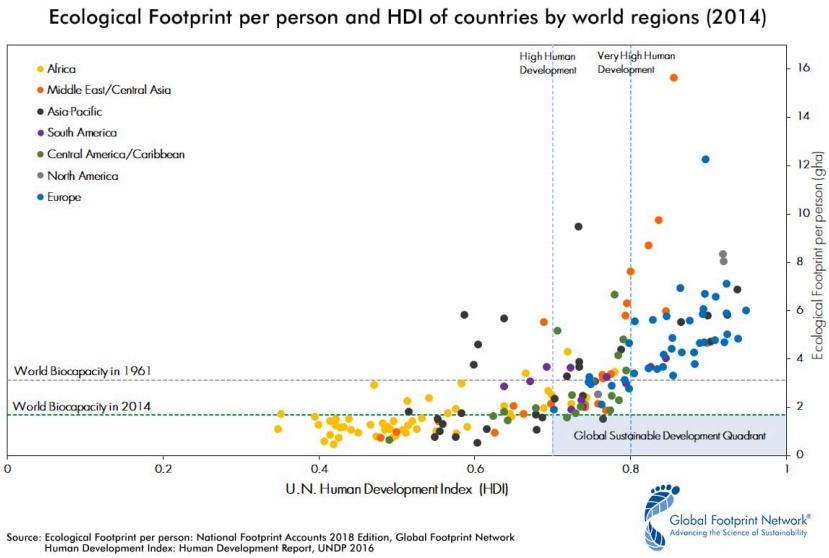

Figure $12.3.b$: The ecological footprint per person in relation to the U.N. human development index for each country coded by region. Countries in some regions of the world have low ecological footprints per person, but this is because people are living in poverty (points in lower left of graph). This pattern is characteristic of many African countries. Other countries have large ecological footprints and live affluently (points in upper right of graph), including many European countries. To sustainably meet human needs, countries must achieve a high human development index and low ecological footprint (points in lower right of graph). Image by Footprint123 (CC-BY-SA).

Are you wondering about the size of your ecological footprint? You can estimate it here.

Regulation

Reducing the population growth rate will limit the consequences of overpopulation; however, regulation of the human population is a complex issue that presents ethical considerations.

Efforts to moderate population control led to the 1979 One-Child Policy in China, which imposed fines on urban couples who had more than one child (figure $12.3.c$). Additionally, only a couple's first child was granted educational and health care benefits. The effectiveness of the policy in limiting overall population growth is controversial, as was the policy itself. Tragically, this policy combined with the desire of many couples to have a male heir led to female infanticide. Furthermore, enforcement of the policy led to human rights abuses including forced sterilizations and forced abortions. Over the years, some restrictions associated with the One-Child Policy were lifted. For example, in 2013, an adult who was an only child was allowed to have two children. The policy ended in 2016, and as of May 2021, each couple is now permitted to have up to three children.

Figure 12.3.c: A poster explaining and promoting the One-Child Policy. Image by Arian Zwegers (CC-BY).

Zero population growth occurs when the birth rate equals the death rate such that the rate of population growth is zero. Logically, this would occur when total fertility rate equals replacement fertility rate, but as described in the previous section, this depends on the age structure of a population.

All else being equal, reductions in total fertility rate will slow human population growth. Total fertility rate is negatively correlated with improved standard of living, access to health care, and gender equality. As countries develop economically, individuals become increasingly dependent on urban jobs rather than the family farm for income and provisions. While a large family would be needed to tend the family farm, supporting many children in an urban area is expensive. As a result, economic development is associated with couples choosing to have fewer children.

Access to healthcare decreases childhood mortality and provides the option of birth control. While decreased infant and childhood mortality alone would increase the population growth rate, people tend to have fewer children when they can be confident that all of their children are likely to survive; thus, as childhood mortality declines, total fertility rate also declines, lowering the population growth rate.

The education of women and girls is also associated with a decreased total fertility rate. Furthermore, family planning education programs have had highly positive effects in some countries on limiting population growth rates and increasing standards of living. When women have knowledge of family planning, power to make decisions about their family size, and a variety of career options, fertility rate declines. In regions that have made recent strides in educating girls, families more often choose to have a small number of children so that they can afford to pay for their education regardless of gender.

References

Population Growth (Annual %). 2019 World Bank Group. Accessed 29 August 2020.

Growing at a slower pace, world population is expected to reach 9.7 billion in 2050 and could peak at nearly 11 billion around 2100. 2019. United Nations Department of Economic and Social Affairs. Accessed 29 August 2020.

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12.4: Data Dive- World Population Densities

Overview

The Socioeconomic Data and Applications Center (SEDAC), is one of the Distributed Active Archive Centers (DAACs) in the Earth Observing System Data and Information System (EOSDIS) of the U.S. National Aeronautics and Space Administration (NASA). Its main objective is to investigate human interactions in the environment and to develop and operate applications that support the integration of socioeconomic and earth science data and to serve as an "Information Gateway" between earth sciences and social sciences. One of the projects it continually updates is creating global population density maps. Their 2020 map can be observed below:

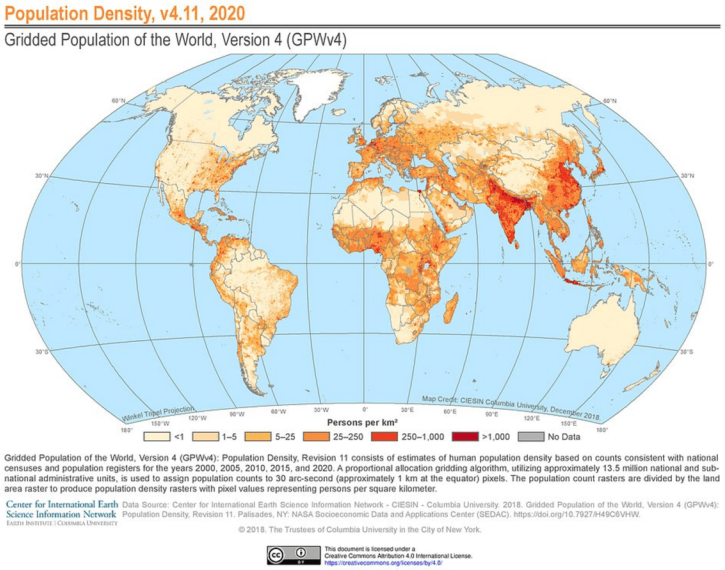

Figure $12.4.a$: World density map. Graph by SEDAC (CC-BY-3.0) Gridded population of the world (version 4) illustrating population density for the year 2020. Density is indicated with darker or lighter shading using the following categories in persons per square kilometer (1, 1-5, 5-25, 25-250, 250-1000, 1000, and no data). North America has highest densities on the east coast of the United States, southern Mexico, Central American countries, and western and eastern coastlines of South America. All of Europe is high density. Africa has the highest densities in countries in the middle of the continent. In Asia, India, eastern China along with Asian islands have very high densities. (CC BY 4.0; The Trustees of Columbia University in the City of New York)

Questions

1. The data on the above graph is overlaid onto a world map. Why do you think this is a powerful way to display data?
2. What question(s) are the authors trying to answer with this graph and table?
3. Which areas of the globe have the highest density levels (darkest density shading)?
4. Are there any areas of the globe that surprise you (either high or low) with their density? Why?
5. How can policy makers/world leaders/health organizations use this information? Provide at least 3 ideas.
6. What is missing from this map? Hint: It's very large!

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12.5: Review

Summary

After completing this chapter you should be able to...

- Discuss the history of human population growth.
- Define demographic transition.
- Explain how total fertility rate and age structure affect current and future population growth rate.
- Interpret age structure diagrams.
- Discuss the long-term implications of unchecked human population growth with respect to carrying capacity and ecological footprints.
- Describe efforts to regulate human population size.

The world's human population is growing at an exponential rate. Humans have increased the world's carrying capacity through migration, agriculture, medical advances, and communication. The age structure of a population allows us to predict population growth. Unchecked human population growth could have dire long-term effects on our environment.

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13: WATER RESOURCES

Chapter Hook

The aqueducts of Rome are a huge feat of ancient achievement and ingenuity. Not only did they provide water for drinking and bathing but contributed to agriculture, hygiene (through sewers and plumbing), culture, and industry. These stone waterways took about 500 years to complete (312 BC to 226 AD) and contributed significantly to the success of Rome. Water is essential for survival, so other ancient civilizations found ways to move water as well; however, none even came close to being as successful or magnificent.

Figure 13.a: Roman aqueduct. Image by Pixabay (Public Domain)

13.1: Fresh Water Supply and the Water Cycle

13.2: Water Usage

13.3: Water Scarcity and Solutions

13.4: Data Dive- Aqueducts of Rome

13.5: Review

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13.1: Fresh Water Supply and the Water Cycle

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.

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 two 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.

Water Reservoirs

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 $13.1.a$ 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.

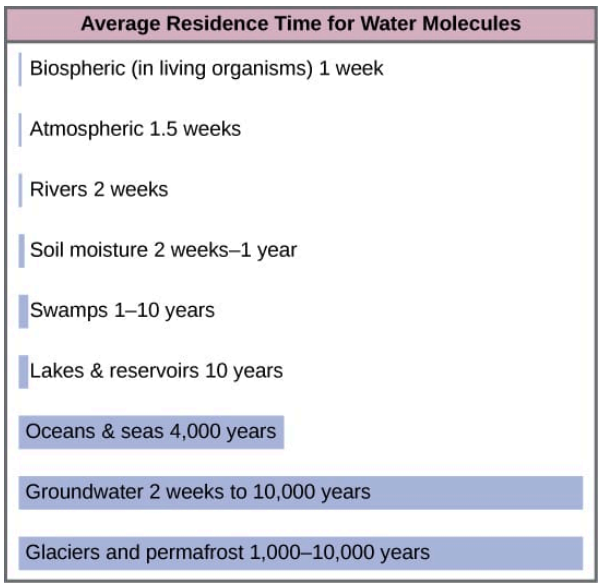

Figure $13.1.a$: Average residence time that water remains in each reservoir. Water remains in organisms for about one week, in the atmosphere for 1.5 weeks, in rivers for two weeks, as soil moisture from two weeks to a year, in swamps for 1-10 years, in lakes for 10 years, in oceans and seas for 4,000 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).

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 71% of Earth's surface is covered by water, and approximately half of Earth's surface is obscured by clouds (also made of water) at any time. There is a very large volume of water on our planet, about 1.4 billion cubic kilometers (km^3) = 330 million cubic miles, or about 53 billion gallons per person on Earth. All of Earth's water could cover the United States to a depth of 145 km (90 mi).

Despite the vast volumes of water on Earth, only 2.5% is fresh water (figure $13.1.b$), and only 0.01% is available for humans to use. 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 2-3 tablespoons. Much of Earth's fresh water is trapped in glaciers and polar ice caps (figure $13.1.c$), and this water is inconveniently located, mostly in Antarctica and Greenland. Shallow **groundwater** (water located below the Earth's surface) is the largest reservoir of usable fresh water. Many organisms are dependent on surface waters,

such as lakes and rivers, which comprise a small fraction of fresh water on Earth. A lack of these surface waters can have negative effects on ecosystems.

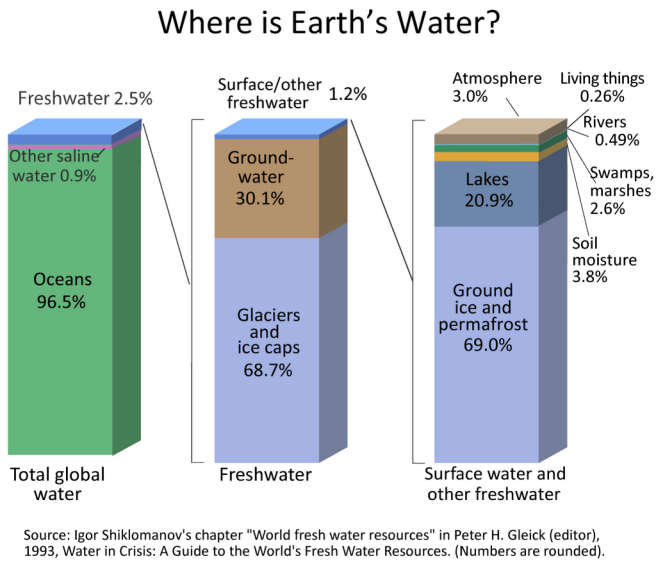

Figure $13.1.b$: Bar chart of the distribution of Earth's water, including total global water, fresh water, and surface water. Oceans are the largest of Earth's water reservoirs, and only 2.5% of Earth's water is fresh water. Most of this fresh water (68.7%) is in glaciers and ice caps, 30.1% is groundwater, and 1.2% is surface and other fresh water. Of this 1.2%, 3.0% is found in the atmosphere, 0.26% in living things, 0.49% in rivers, 2.6% in swamps and marshes, 3.8% as soil moisture, 20.9% in lakes, and 69.0% as ground ice and permafrost. Image from USGS/Igor Shiklomanov (public domain).

Figure $13.1.c$: 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

The Water Cycle

The **water cycle** (hydrologic cycle) shows the movement of water through different reservoirs, which include oceans, atmosphere, glaciers, groundwater, lakes, rivers, and organisms (figure $13.1.d$). Solar energy, which warms the oceans and other surface waters, and gravity drive the motion of water in the water cycle. This leads to **evaporation** (liquid water to water vapor) of liquid surface water, **sublimation** (ice to water vapor) of frozen water, and **transpiration** (the loss of water from plants to the atmosphere). When water in the soil is taken up by plant roots, it moves through tubes in the plant (the vascular system), evaporates within the space of the leaf, and transpires through the stomata (small microscope openings) of the leaves. Ecologists combine transpiration and evaporation into a single term that describes water returned to the atmosphere: **evapotranspiration**. Thus, large amounts of

water move into the atmosphere as water vapor.

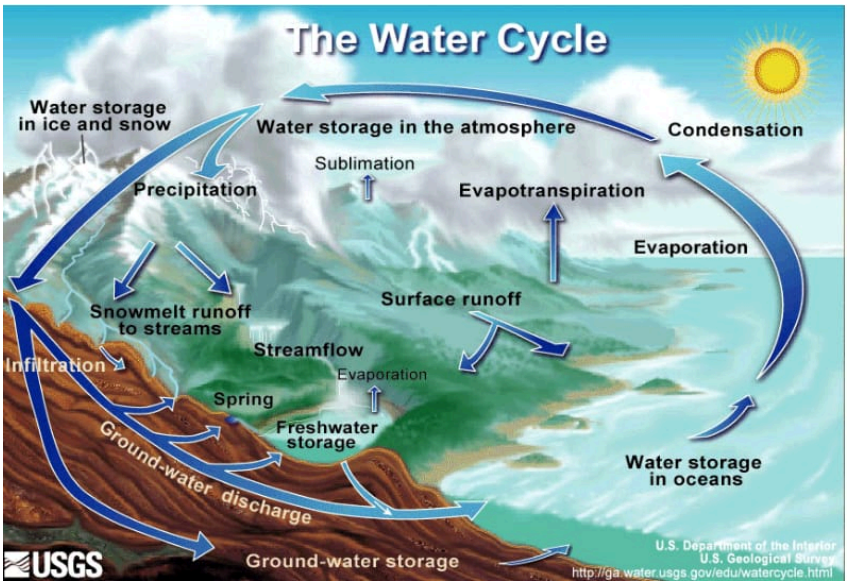

Figure 13.1.d: The water cycle. Arrows depict movement of water to different reservoirs located above, at, and below Earth's surface. Evapotranspiration and sublimination add water to the atmosphere, where it condenses to form clouds. Water is thus stored in the atmosphere. Through precipitation, water returns to the Earth's surface. When precipitation occurs at high elevation, water is stored as snow or ice. When the snow melts, the resultant runoff can add to streams. Water from precipitation can also infiltrate to replenish groundwater storage or form surface runoff. Groundwater discharge, water from streams, and surface runoff flows into bodies of fresh water and ocean. Source: United States Geological Survey

Water vapor in the atmosphere can migrate long-distances from ocean to over land by way of prevailing winds. Over the ocean or land, the air can cool and cause the water to **condense** back into liquid water. This usually happens in the form of very small water droplets that form around a microscopic piece of dust or salt called condensation nuclei. These small water droplets are visible as a cloud. Clouds build and once the water droplets are big enough, they fall to earth as **precipitation** (rain, snow, hail, or sleet), which returns water to Earth's surface.

Precipitation that reaches land can immediately return to the atmosphere, add to groundwater, or form surface runoff. 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 or directly from the soil surface. Groundwater is replenished when water **infiltrates** into the soil and finally fills the pore spaces between particles in dirt, sand, and gravel or in the fissures in rocks. Groundwater slowly moves through rock and unconsolidated materials and some of it eventually reaches the surface again, where it discharges as springs and into streams, lakes, and the ocean. Many streams flow not because they are replenished from rainwater directly but because they receive a constant inflow from the groundwater below. Also, surface water in streams and lakes can infiltrate again to recharge groundwater. Therefore, the surface water and groundwater systems are connected. Groundwater can also ultimately flow into the ocean through subsurface groundwater flow, but some groundwater is found very deep in the bedrock and can persist there for millennia. **Surface runoff** is the flow of fresh water over land either from rain or melting ice. Runoff can make its way through streams and lakes to the oceans. Surface runoff will occur only if the soil becomes saturated with water in a heavy rainfall.

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

Salinity and the Water Cycle

An important part of the water cycle is how water varies in salinity, which is the abundance of dissolved ions in water. The salt water 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. The environmental effects of runoff were discussed in Biogeochemical Cycles. Fresh water (such as lakes, rivers, and near-surface groundwater) has a relatively low salinity.

Human Interactions with The Water Cycle

Humans alter the water cycle by extracting large amounts of fresh water from surface waters as well as groundwater (see Water Usage). Additionally, changes in land use, such as deforestation, agriculture, and urbanization, reduce vegetation cover, which reduces infiltration and increases surface runoff. (Vegetation naturally traps precipitation as it falls, slows the flow surface runoff, and increases the infiltration rate.) This intensifies flooding and exacerbates erosion, lowering soil quality and causing sediment pollution in water. Additionally, humans redirect the flow of water by building dams and aqueducts (figure $13.1.e$). 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 $13.1.e$: The California Aqueduct carries water needed for agriculture from Northern California to Southern California. Image by USGS (public domain).

Water Resources

Freshwater resources are ultimately replenished by precipitation. This water can then be obtained from surface water, such as rivers and lakes, and from aquifers, which store groundwater.

Primary Fresh Water Resources: Precipitation

Precipitation levels are unevenly distributed around the globe, affecting fresh water availability (figure $13.1.f$). In general, due the uneven heating of the Earth and global air circulation cells resulting from the Earth's rotation, air rises near the equator and near 60° north and south latitude and sinks at the poles and 30° north and south latitude. As discussed in Climate Effects on Biomes, 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.

The size of continents, mountains, prevailing winds, ocean circulation patterns, and even the proximity of bodies of water can affect local climate patterns. For example, when cold winds blow across the relatively warm Great Salt Lake, the air warms, which causes it to pick up moisture. This local increase in the moisture content of the air may eventually fall as snow or rain on nearby mountains, a phenomenon known as “lake-effect precipitation”.

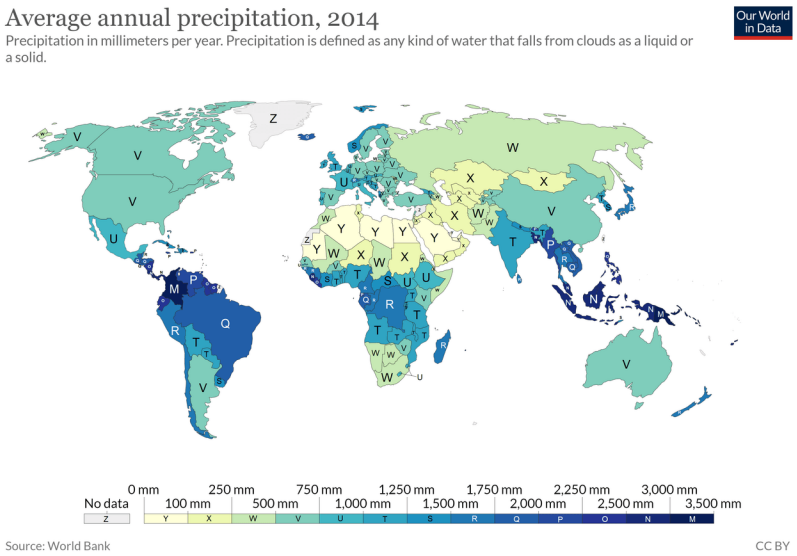

Figure $13.1.f$: Annual average precipitation by country in 2014. Countries with the highest rainfall (3000-3500 mm) are Nicaragua, Costa Rica, Panama, Columbia, Sierra Leone (in West Africa), Bangladesh, and many of the islands is Southeast Asia. Countries with the least rainfall (0-100 mm) are Saudi Arabia and several North African countries. The United States has intermediate rainfall (500-750 mm). The world's rainforests grow in areas with high rainfall while areas with very little rainfall are deserts. Image modified from Our World in Data/World Bank (CC-BY).

In the United States, the 100th Meridian roughly marks the boundary between the humid and arid parts of the country (figure $13.1.g$). Irrigation is required to grow crops west of the 100th Meridian. In the West, surface water is stored in reservoirs (artificial lakes) and mountain snowpacks and strategically released through a system of canals during times of high use.

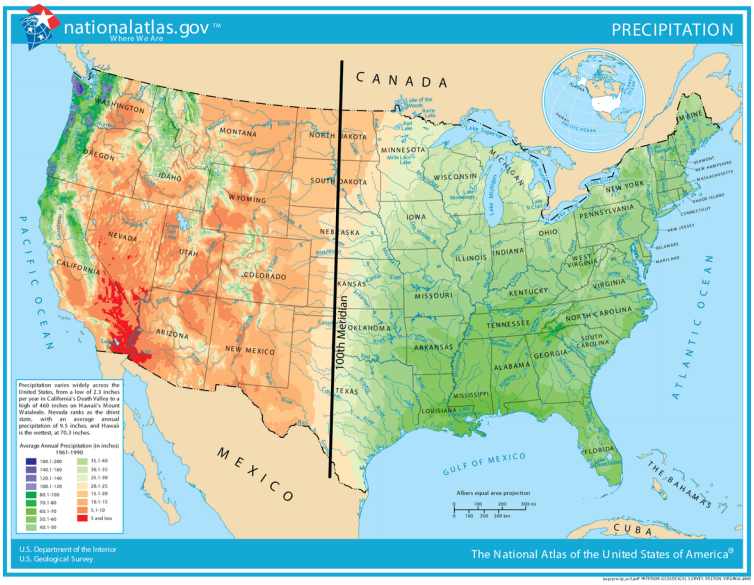

Figure $13.1.g$: Distribution of precipitation in the United States. The 100th Meridian is approximately where the average precipitation transitions from relatively wet to dry. Eastern states are mostly green, indicating greater precipitation than most western states, which are mainly orange or red (indicating low precipitation). (Source: U.S. Geological Survey)

Surface Water: Rivers and Lakes

Rivers are an important water resource for irrigation of cropland and drinking water for many cities around the world. Flowing water from rain and melted snow on land enters river channels by surface runoff (figure $13.1.h$) and seepage from surrounding land. The geographic area drained by a river and its tributaries is called a **watershed**. The Mississippi River watershed includes approximately 40% of the U.S., a measure that includes the smaller watersheds, such as the Ohio River and Missouri River that help to comprise it. 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 $13.1.h$: Surface runoff, part of overland flow in the water cycle Source: James M. Pease at Wikimedia Commons

In addition to rivers, lakes can also be an excellent source of fresh water for human use. They usually receive water from surface runoff and groundwater. By building dams, people create artificial lakes (**reservoirs**).

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. A large area of subsurface, porous rock unit or sediment that holds extractable groundwater is an **aquifer**. The **saturated zone** of an aquifer is where groundwater completely fills pore spaces in earth materials. The **water table** is the uppermost level at which the pores are fully saturated with water (figure $13.1.i$).

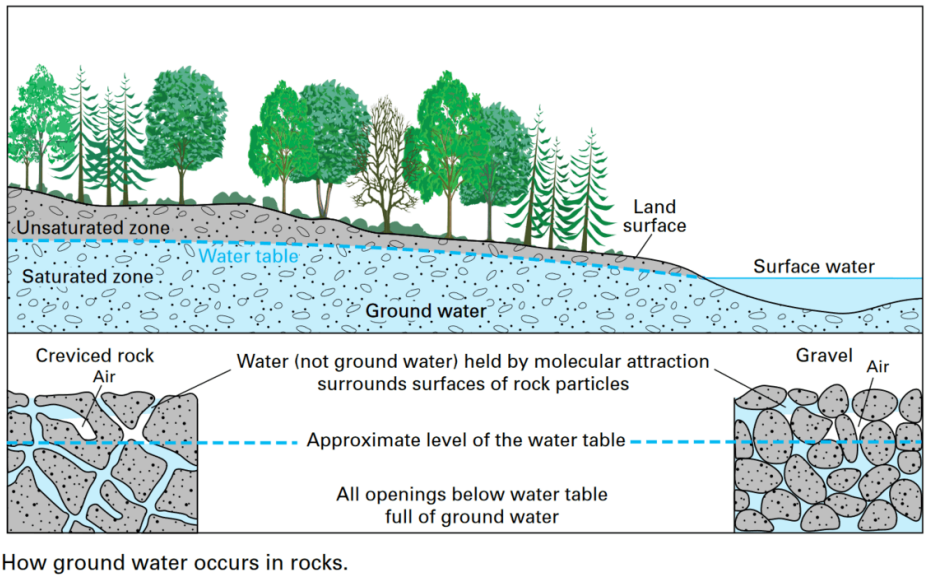

Figure $13.1.i$: The unsaturated and saturated zones of an aquifer, which stores groundwater. The water table is the upper level of the saturated zone. The land surface is covered in vegetation, and the top of the surface water is continuous with the water table. The bottom of the image shows creviced rock (left) and gravel (right), both of which contain spaces that store air and water. Above the water table, water (not groundwater) is held by molecular attraction and surrounds the surfaces of rock particles. All openings below the water table are full of water table. Image by USGS (public domain)

A combination of a place to put water (porosity) and the ability to move water (permeability) makes a good aquifer. **Porosity** is

a measure of the open space in rocks –expressed as the percentage of open space that makes up the total volume of the rock or sediment material. **Permeability** is a measure of the interconnectedness of pores in a rock or sediment. The connections between pores allows for that material to transmit water. Porosity and permeability are functions of soil particle composition. For example, clays generally have very high porosity, but the pores are poorly connected, thereby causing low permeability.

Aquifers are commonly drilled, and wells installed, to provide water for agriculture and personal use. In many cases aquifers are being depleted faster than they are being replenished by water infiltrating down from above. 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.

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** (figure $13.1.j$). 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.

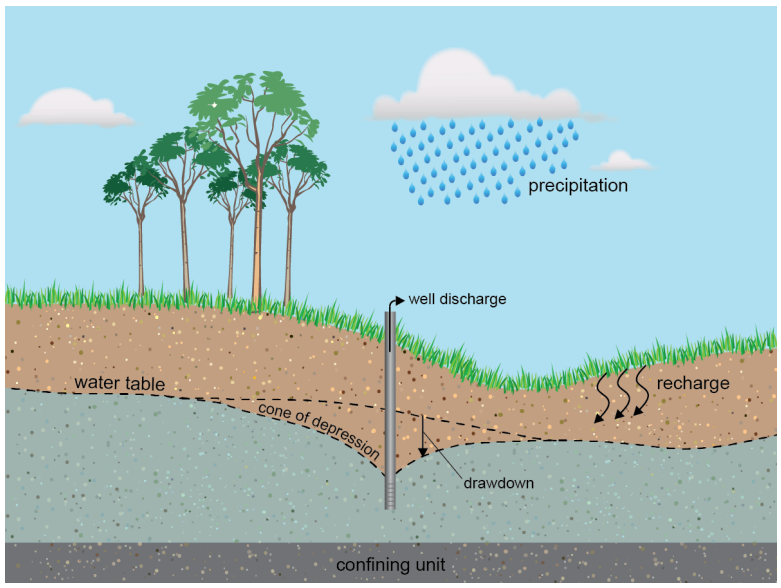

Figure $13.1.j$: As groundwater is extracted from the well, the water table of the aquifer dips, forming a cone of depression. Drawdown is between the water table and the cone of depression. Precipitation is represented by water droplets falling from a cloud. It soaks into the ground, recharging the aquifer. At the bottom of the aquifer is the confining unit, which is impermeable to water. Image by Tara Gross/USGS (public domain).

Another water resource problem associated with groundwater mining is **saltwater intrusion**, where overpumping of freshwater aquifers near ocean coastlines causes salt water to enter freshwater zones. The drop of the water table around a cone of depression in an 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. Because the pores in the aquifer collapse as subsidence occurs, this permanently reduces the capacity of the aquifer to hold water in the future.

Groundwater is replenished through infiltration, 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 into the ground rather than running into rivers or evaporating (figure $13.1.k$). Recharge areas are generally the topographically highest location of an aquifer. They are characterized by streams that lie below the water table and sediment or rock that allows infiltration into the subsurface. Wetlands, for example, are excellent recharge areas. Recharge areas mark the beginning of groundwater flow paths.

Recharge can be induced through the aquifer management practice of aquifer storage and recovery. Injection wells allow for humans to increase the rate of recharge into an aquifer system by pumping water into an aquifer (figure $13.1.k$). Injection wells are regulated by state and federal governments to ensure that the injected water is not negatively impacting the quality or supply of the existing groundwater in the aquifer. Some aquifers are capable of storing significant quantities of water, allowing water managers to use the aquifer system like a surface reservoir. Water is stored in the aquifer during periods of low water demand

and high water supply and later extracted during times of high water demand and low water supply.

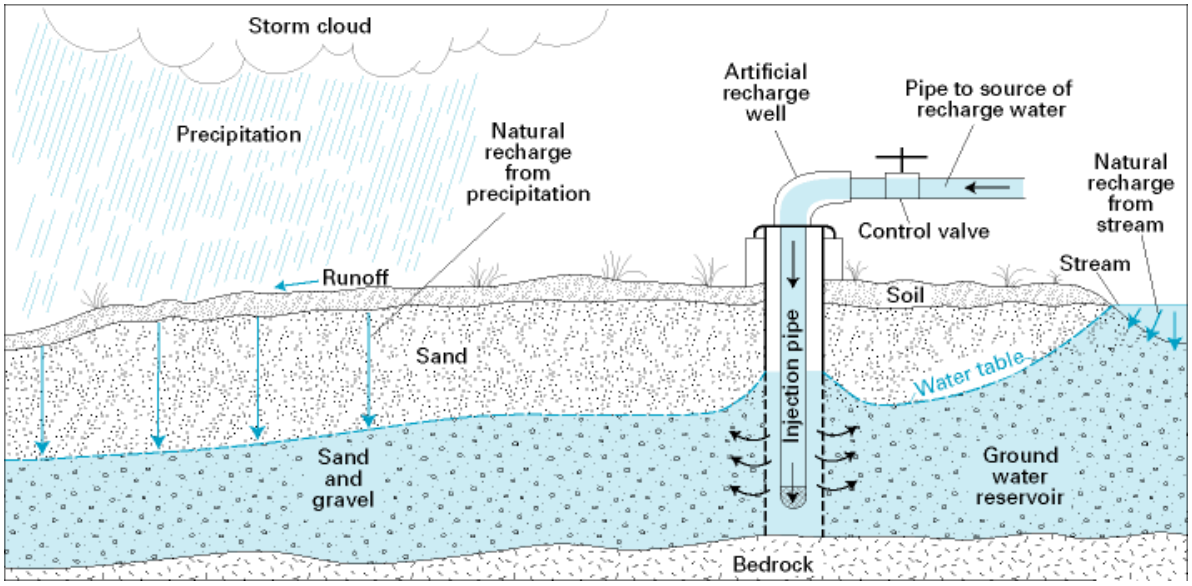

Figure 13.1.k: Groundwater can be replenished through natural recharge areas as well as artificial injection wells. In this diagram, precipitation emerges from a storm cloud. Some of the water washes away as runoff, and some water infiltrates through the sand (natural recharge from precipitation). The water fills the sand and gravel in the aquifer (labeled ground water reservoir). Below the aquifer is bedrock, which is impermeable to water. Another natural source of recharge is from streams. Through an artificial recharge well, water flows from a pipe through a control valve into an injection pipe. This also adds to the groundwater. Image by USGS (public domain).

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13.2: Water Usage

Freshwater supply is one of the most important ecosystem services. In 2014, global water consumption was 3999 km^3 per year (over 1,000 trillion gallons!). 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 (figure $13.2.a$).

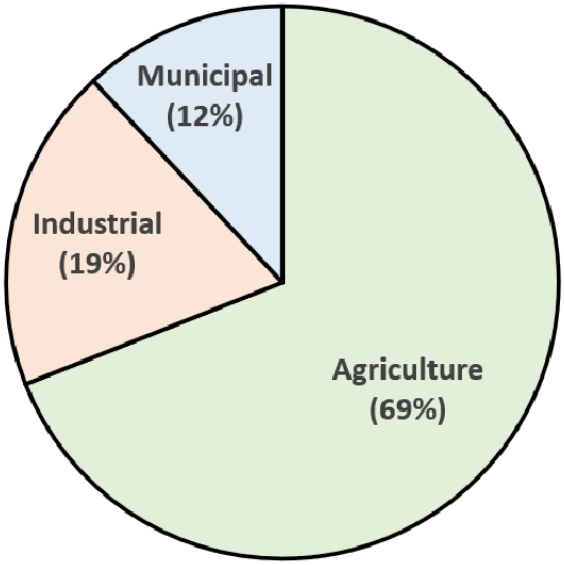

Figure $13.2.a$: Global water usage by sector. Municipal refers to domestic use, such as by local businesses and households. Data from FAO. Image by Melissa Ha (CC-BY-NC).

Humans require only about 1 gallon per day to survive, but a typical person in a U.S. household uses approximately 80-100 gallons per day, which includes cooking, washing dishes and clothes, flushing the toilet, and bathing. Additionally, we rely on the food, energy, and mineral resources, which all require water to produce. For example, approximately three gallons are needed to produce a tomato, 150 gallons for a loaf of bread, and 1,600 for a pound of beef. (You can learn more about the water footprint of different foods using this interactive website.) Twenty-one gallons are needed to produce one kilowatt-hour (kWh) of electricity from a traditional power plant (about 1 kWh is needed to heat an oven for 30 minutes), and one ton of steel consumes about 63,000 gallons of water. The **water demand** of an area is a function of the population and other uses of water.

In the United States, 281 billion gallons of water were withdrawn per day in 2015, of which 82 billion gallons are fresh groundwater (figure $13.2.b$). The state of California accounts for 9% of national water withdrawal (figure $13.2.c$).

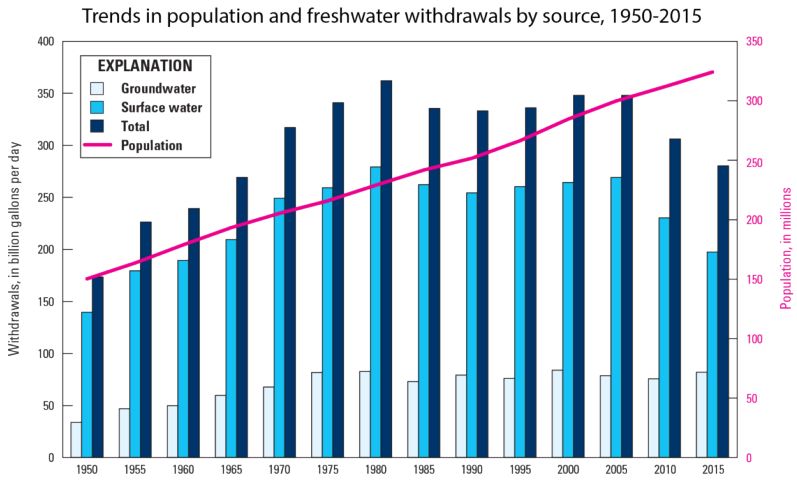

Figure $13.2.b$: Average daily freshwater withdrawals (in billion gallons per day, left y-axis) over time (x-axis) in the United States. Light blue bars (left) represent groundwater withdrawals, medium blue (middle) represents withdrawals from surface water, and dark blue bars (right) represent total withdrawals in billions of gallons per day. In 1950, total withdrawals were around 170 billion gallons per day. This gradually increased until 1980 at just over 350 billion gallons per day. In 1985, total withdrawals dropped to around 325 billion gallons and stayed relatively constant until decreasing in 2010. In 2015, total withdrawals were around 260 billion gallons. Most of the changes in withdrawals overtime were due to changes in surface water withdrawals rather than groundwater withdrawals. Surface water withdrawals have generally been 2-3 times greater than groundwater withdrawals. The pink line represents the United States population size in millions (right y-axis), which has increased from roughly 170 million in 1950 to about 325 million in 2015. Image by USGS (public domain).

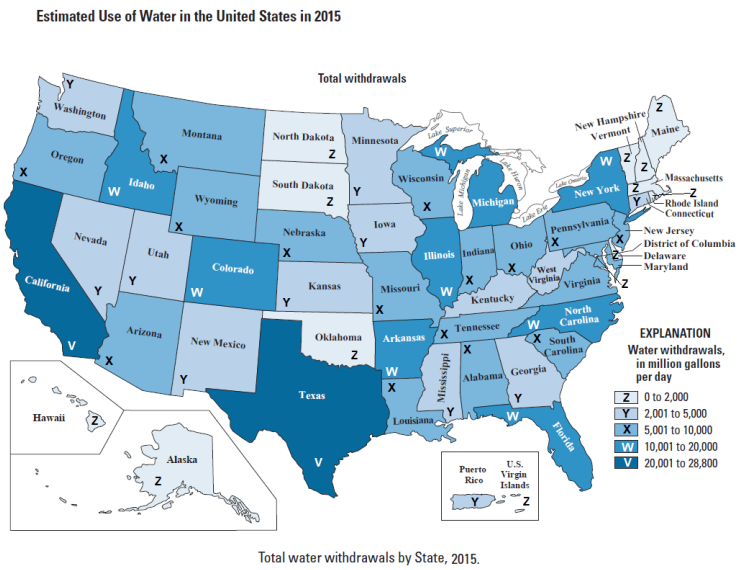

Figure $13.2.c$: Total water withdrawals by state in 2015. The lightest blue (Z) indicates 0-2,000 million gallons per day, and the darkest blue (V) indicates 20,001-28,800 million gallons per day. California and Texas consume the most water, and Alaska, Hawaii, the Dakotas, Oklahoma, and some New England states consume the least. Image modified from USGS (public domain).

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13.3: Water Scarcity and Solutions

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.

Water Scarcity

The **water crisis** refers to a global situation where people in many areas lack access to sufficient water, clean water, or both. 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, water overuse, water pollution, and climate change. Specifically, climate change shifts precipitation patterns and causes the snow pack that recharges rivers to melt earlier in the year. Furthermore, rising sea levels associated with climate change worsen saltwater intrusion.

Water scarcity refers to water shortages, which can be physical or economic (figure $13.3.a$). **Physical water scarcity** is the lack of sufficient water resources in an area; that is, water is depleted more quickly than it is replenished. Unpredictable precipitation patterns associated with climate change, which increase the risk of flooding and drought, exacerbates physical water scarcity. **Economic water scarcity** occurs when people cannot afford access to water. The United Nations estimates that over half of the global population faces water scarcity for one or more months of the year (see The Sustainable Development Goals Report 2019). According to the World Health Organization and UNICEF, 785 million people lack access to even a basic drinking water service (see Drinking Water) and two billion people lack access to improved sanitation as simple as a pit latrine (see Sanitation), and three billion people lack a facility to wash their hands (see Hand Hygiene for All). As a result, nearly 829,000 people die every year from diarrheal diseases, and 297,000 of those deaths occur among children under the age of five (see Drinking Water).

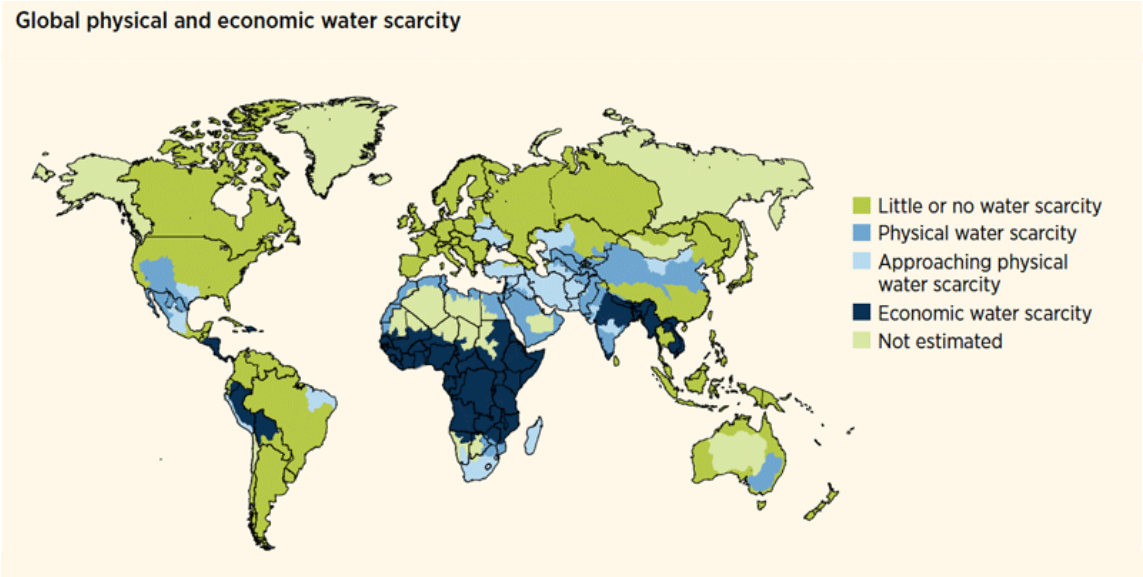

Figure $13.3.a$: Regions facing or approaching water scarcity in 2012. Physical water stress occurs in the southwestern United States, the Middle East, North Africa, southern India, and southeast Australia. Economic water stress occurs in Central and East Africa, western India, and Southeast Asia. Image by World Water Assessment Programme (WWAP; public domain).

Solutions for Addressing Water Shortages

While some human activities have exacerbated the water crisis, humans have also developed technologies to better acquire or conserve freshwater. Solutions to addressing water shortages include dams and reservoirs, rainwater harvesting, aqueducts, desalination, water reuse, and water conservation.

Dams and Reservoirs

Reservoirs (artificial lakes) that form behind dams in rivers can collect water during wet times and store it for use during dry spells (figure $13.3.b$). 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 and downstream river channel erosion. Additionally, dams reduce water flow downstream, which could lead to political conflicts when rivers span states or countries.

The negative ecosystem impacts of dams are another major drawback. For example, dams change a river to a lake habitat and interfere with migration and spawning of fish. Furthermore, warming of the surface water in the reservoir influences the temperature of the water downstream, impacting the fish and aquatic invertebrates that are adapted to colder water. Dams also trap sediments that would otherwise continue to flow down the river, creating habitat and supplying nutrients downstream.

Figure $13.3.b$: The Hoover Dam on the Colorado River in Nevada. Behind the dam is Lake Mead, the largest reservoir in the United States. Image by Dsimic (CC-BY-SA).

Rainwater Harvesting

Rainwater harvesting involves catching and storing rainwater before it reaches the ground. Figure $13.3.c$ shows a complex rainwater harvesting system (rain water capture system) proposed for federal buildings, but smaller, simpler systems (sometimes called rain barrels) can be used by individual homeowners (figure $13.3.d$).

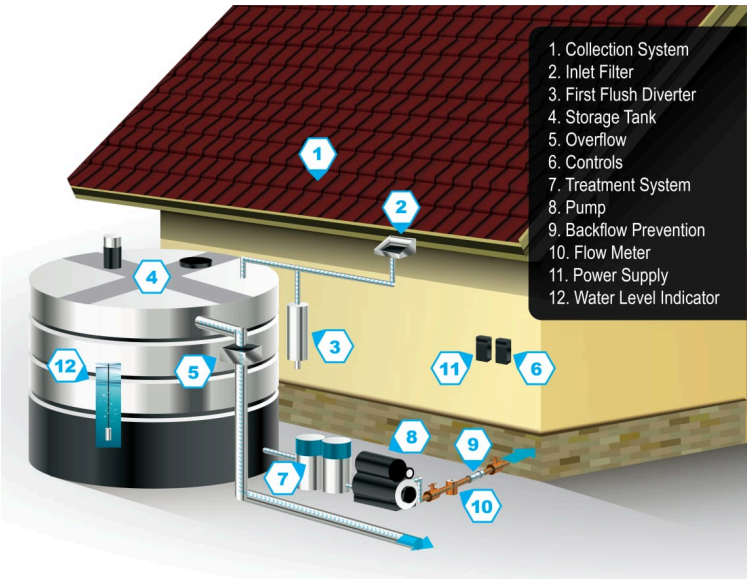

Figure 13.3.c: The components of a rainwater harvesting system include (1) the collection system consisting of the roof surface and gutters that capture rain water and send it to (2) the inlet filter, a screen that catches large debris. (3) The first flush diverter removes debris not captured by the inlet filter from the initial stream of rainwater. (4) The storage tank is composed of food-grade polyester resin material approved by the U.S. Food and Drug Administration (FDA), which is green in color and helps to reduce bacterial growth. (5) The overflow is a drainage spout that releases excess water if the storage tank is full. The (6) control system monitors the water level and filtration system, and the (7) treatment system is responsible for filtration and disinfection, treating water until it is potable (safe to drink). The (8) pump moves water through the system to where it will be used, and the (9) backflow preventer ensures that water cannot flow backwards through the system in cases of low water pressure (when the storage tank is low). (10) The flow meter (with data logger) measure water production. The (11) power supply may rely on conventional energy sources or solar energy, and the (12) water level indicator monitors the water level in the storage tank. Caption modified from and image from Office of Energy Efficiency and Renewable Energy, Department of Energy (public domain).

Figure 13.3.d: A rain barrel is a simple rainwater harvesting system. Homeowners commonly use the stored water to irrigate their gardens. Image by Walton LaVonda, USFWS (public domain).

Aqueducts

Aqueducts can move water from where it is plentiful to where it is needed. Aqueducts can be controversial and politically difficult especially if the water transfer distances are large. One drawback is the water diversion can cause drought in the area from where the water is drawn. For example, Owens Lake and Mono Lake in central California began to disappear after their river flow was diverted to the Los Angeles aqueduct (figure 13.3.e). Without water supply, Owens Lake dried and became a major source of particulate matter, polluting the air during dust storms (see Air Pollution). Owens Lake remains almost completely dry, but

Mono Lake has recovered more significantly due to legal intervention. Learn more about the Los Angeles Aqueduct here.

Figure $13.3.e$: The Los Angeles Aqueduct diverts the flow of several eastern California rivers to the city of Los Angeles. Image by Los Angeles (CC-BY-SA).

Desalination

One method that can actually increase the amount of freshwater on Earth is **desalination**, which involves removing dissolved salt and minerals from seawater or saline groundwater (figure $13.3.f$). An advantage of this approach is that there is a virtually unlimited supply of saltwater. There are several ways to desalinate seawater including boiling, filtration, electrodialysis (applying an electric current to removed the ions which comprise salts), and reverse osmosis (figure $13.3.g$). All of these procedures are moderately to very expensive and require considerable energy input, making the water produced much more expensive than freshwater 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 $13.3.f$: Port Stanvac Desalination Plant under construction in South Australia. Image by Vmenkov (CC-BY-SA).

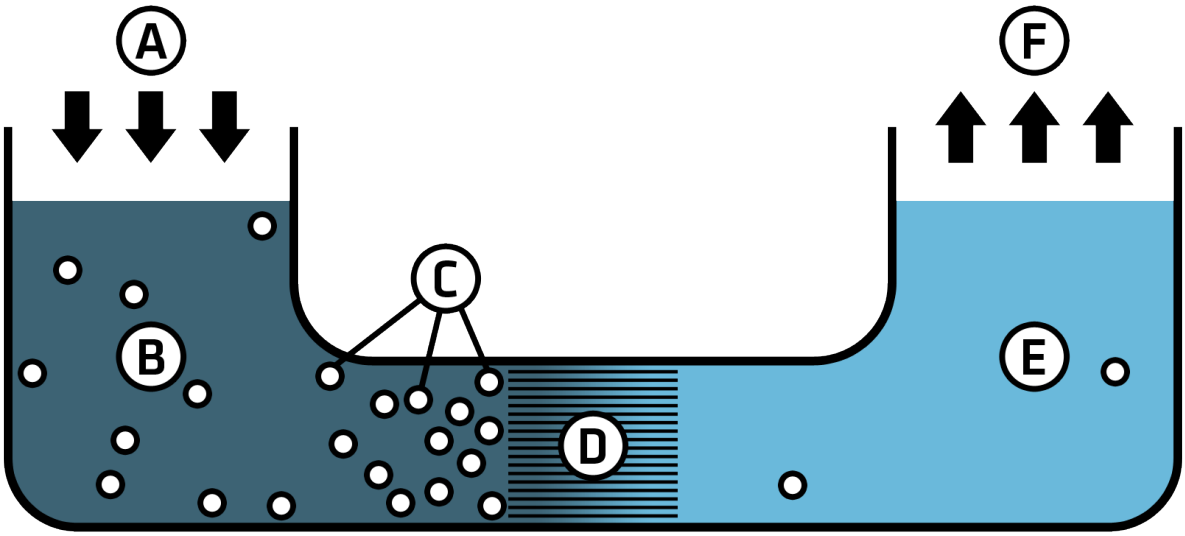

Figure $13.3.g$: Reverse osmosis is one method of desalination. In this process, pressure (A) is applied to salt water, which contains ions (charged atoms or molecules) and other contaminants (C). The water is forced through a semipermeable membrane (D), through which the contaminants cannot pass. Clean freshwater that is safe to drink (E) is then distributed (F). Image by Colby Fisher (CC-BY-SA).

Water Reuse (Water Recycling)

Water recycling refers to reusing water for appropriate purposes such as agriculture, municipal water supply, industrial processes, and environmental restoration (figure $13.3.h$). This could occur at the scale of a single household, for example, installing plumbing that reroutes water drained from the sink to flush the toilet. Water recycling can also occur at large scales. For example, wastewater from the sewage system is regularly treated to an extent, but it can be treated further to produce **potable water** (which is safe to drink) and then pumped into depleted aquifers. This approach limits saltwater intrusion of aquifers near the coast and reduces dependence on precipitation and subsequent infiltration to recharge aquifers. Orange County Water District in California employed this system following an information campaign to explain the purification process and ensure public confidence in the safety of the treated wastewater.

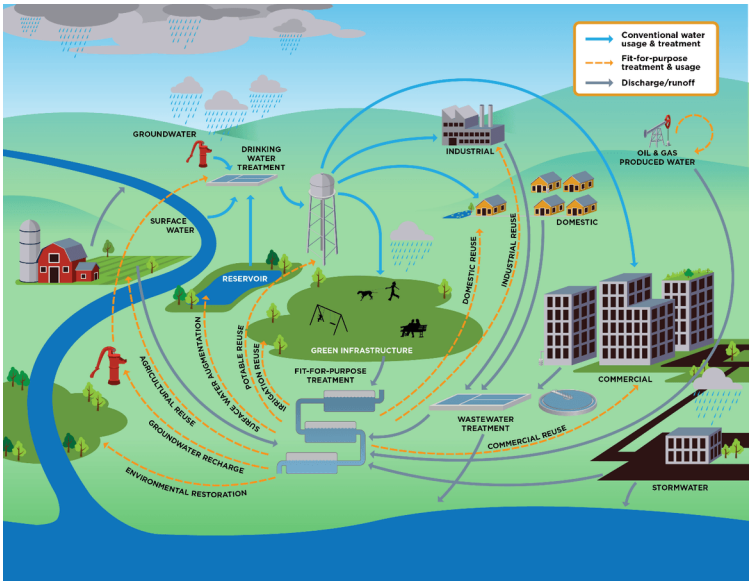

Figure $13.3.h$: Flowchart of water reuse. Surface water, groundwater, and water from reservoirs undergoes drinking water treatment. From there, it serves commercial, industrial, and domestic purposes and supports green infrastructure. Used water is treated to the extent needed for its purpose (fit-for-purpose treatment). Fit-for-purpose treatment and usage include environmental restoration, ground water recharge, agricultural reuse, surface water augmentation, portable reuse, irrigation reuse, domestic reuse, industrial reuse, and commercial reuse. Discharge from industrial, domestic, and commercial buildings is processed through wastewater treatment. Image by EPA (public domain).

Water Conservation

Water conservation refers to using less water and using it more efficiently. Around the home, conservation can involve both water-saving technologies and behavioral decisions. Examples of water-saving technologies include high-efficiency clothes washers and low-flow showers and toilets. Water-conserving behaviors include turning off the water while you brush your teeth, taking shorter showers and showers instead of baths, and fixing leaky faucets. A dishwasher uses less water than washing dishes by hand, particularly the dishwasher is only run when it is full. Similarly, running fewer, larger loads of laundry conserves water relative to more frequent, smaller loads. Choosing foods with a low water footprint (like eggs) over those with a high water footprint (like beef) can also conserve water.

Gardening offers several water-saving opportunities. If you live in a dry climate, consider growing only native, drought-tolerant vegetation, which requires little irrigation (figure $13.3.h$). When you do irrigate your garden, do so only as needed and early in the morning, when less water will be lost to evaporation. Drip systems assist in delivering only the needed amount of water in a way that minimizes evaporation. These strategies can also be applied at large scales in agriculture, which is extremely important considering the high agricultural demands on our water supply relative to municipal use. 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, and no-till farming, which reduces evaporative losses by covering the soil.

Figure $13.3.i$: Using water-efficient plants and irrigation not only looks beautiful, but saves resources and supports biodiversity and natural pollinators. Image and caption from CA Department of Water Resources (public domain).

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. (Purchasing a water filter is a more sustainable solution than bottled water if you do not like the taste of tap water.)

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13.4: Data Dive- Aqueducts of Rome

Overview

All drinking water sources are subject to contamination that require appropriate treatment to eliminate disease-causing pathogens. Sources of water contamination can originate from naturally occurring chemicals and minerals (arsenic, radon, uranium), local land use practices (fertilizers, pesticides), manufacturing processes, and sewage. If left untreated, the presence of contaminants in water can lead to adverse health effects, both acute and chronic. This is why the achievement of the aqueducts of Rome are so astounding! Not only did they water to the residents of Rome, but somehow the Romans were able to identify the cleanest water sources for drinking without the most basic testing equipment. In 1995 Peter Aicher published a book titled, "Guide to the aqueducts of ancient Rome." The book discusses a lot of the history surrounding the 11 aqueducts while also integrating a more modern analysis of the quality of the water based on where it was sourced. The table below provides a brief overview of the aqueducts along with several notes about their use:

Table $13.4.a$**:** Aqueduct characteristics and notes about water volume, source, quality and use. Table by Rachel Schleiger (CC-BY-NC) modified from data in Aicher PJ 1995.

Aqueduct	Construction Complete	Volume (units)	Water Source	Water Quality	Notes
Appia	312 BC	31	Springs	Good	All underground except inside walls 70% for civic/ imperial uses
Anio Vetus	272-269 BC	74	River	Poor	Used for baths, gardens, and industry
Marcia	144-240 BC	78	Springs	Best	Pure/cold/hard water Supplied baths
Tepula	126-125 BC	7	Streams	Good	Warm water (60F)
Julia	33 BC	20	Springs	Good	N/A
Virgo	22-19 BC	41	Marsh	Good	Almost all underground, some along channel Supplied baths
Alsietina	2 BC	7	Lake	Poor	Build to supply basin for mock sea battles
Claudia	38-52 AD	76	Springs	Good	Built several branches in the city

Aqueduct	Construction Complete	Volume (units)	Water Source	Water Quality	Notes
Anio Novus	38-52 AD	78	River	Okay	Quality was poor until later improved
Traiana	109 AD	47	Springs	Good	N/A
Alexandria	226 AD	9	Springs	Good	Served baths

Questions

1. How many of the 11 aqueducts do you think have drinkable water?
2. Does the above answer surprise you? Why/why not?
3. How many of the aqueducts with drinkable water come from a higher volume aqueduct?
4. Based on what you can observe in the notes, what did the Romans do when water wasn't drinkable?
5. What is the most surprising thing to you about the data presented in the above table? Why?

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13.5: Review

Summary

After completing this chapter you should be able to...

- Describe the different water reservoirs and identify which of these reservoirs are accessible to humans.
- Diagram the water cycle and explain how humans interact with the water cycle.
- Explain how groundwater is acquired from aquifers and how aquifers are recharged.
- Identify the main water-consuming sectors and their relative contributions to water usage.
- Compare physical and economic water scarcity.
- Outline strategies for addressing water shortages.
- Provide examples of water conserving technologies and behaviors.

Water is stored in **water reservoirs**. Although there is much water on Earth, only a fraction of this is freshwater that is accessible to humans. The **water cycle** describes the movement of water through each reservoir and involves **sublimination** and **evapotranspiration**, **condensation**, **precipitation**, **infiltration**, and **surface runoff**. Humans alter the water cycle through land use and diverting water flow. 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 30 degrees latitude, where the world's largest deserts are located. **Surface waters**, including lakes are rivers, are an important source of freshwater. Additionally, **groundwater** can be extracted from **aquifers**. Agriculture is the greatest consumer of water, followed by industry and municipal use.

The **water crisis** refers to a global situation where people in many areas lack access to sufficient water or clean water or both. **Physical water scarcity** occurs when water resources are insufficient, but people face **economic water scarcity** when they cannot afford access to water. Partial solutions to the water crisis include dams and reservoirs, rainwater harvesting, aqueducts, desalination, water reuse, and water conservation.

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14: AGRICULTURE

Chapter Hook

Steep mountain landscapes aren't an ideal place for farming. Yet, for thousands of years farmers in mountainous regions all over the world have grown crops, even on some of the steepest slopes. To accomplish this effectively, farmers needed to carve gigantic steps across mountainous contours, forming terraces. These terraces create enchanting ripple like patterns across the landscape and make one almost forget that these farms are meant to help feed local and global communities.

Figure $14.a$: Terraced rice fields. Image by PxHere (Public Domain).

Since the transition to agriculture 10,000 years ago, human communities have struggled against the reality that soil suffers nutrient depletion through constant plowing and harvesting (mostly nitrogen loss). The specter of a significant die-off in human population owing to stagnant crop yields was averted in the 1970s by the **Green Revolution**, which, through the engineering of new crop varieties, large-scale irrigation projects, and the massive application of petroleum-based fertilizers to supplement nitrogen, increased staple crop production with such success that the numbers suffering malnutrition actually declined worldwide in the last two decades of the 20th century, from 1.9 to 1.4 billion, even as the world's population increased at 100 times background rates. The prospects for expanding those gains in the new century are nevertheless threatened by the success of industrial agriculture itself. Soil depletion, declining water resources, and the diminishing returns of fertilizer technology—all the products of a half-century of industrial agriculture—have seen increases in crop yields level off.

Thumbnail image - Women farmers planting a rice field in West Sumatra.

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Modified by Melissa Ha and Rachel Schleiger from The Industrialization of Nature: A Modern History (1500 to the present) from *Sustainability: A Comprehensive Foundation* by Tom Theis and Jonathan Tomkin, Editors. Download for free at CNX. (licensed under CC-BY)

14.1: Food Security
14.2: Industrial Agriculture
14.3: Selective Breeding and Genetic Engineering
14.4: Sustainable Agriculture
14.5: Data Dive- Landslides and Ag Terraces
14.6: Review

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14.1: 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. In 2019, 690 million people in the world (8.9%) were undernourished (lacked sufficient calories; see The State of Food Security...), and 8.2% of the global population lived in poverty (see Goal 1...). Poverty is internationally defined as living on less than $1.90 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. 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 (corn), and cassava (figure $14.1.a$).

Figure $14.1.a$: Cassava tubers are a staple food crop in tropical regions. Image by Renatosjoao (CC-BY-SA).

Food Security

An individual must have access to food in ample quantity and of sufficient nutritional quality at all times to be **food secure**. Those who never have sufficient quality food are **chronically food insecure**. Food security is determined by availability, access, and utilization.

Food availability refers to whether enough food is produced globally to feed the world's population. In fact, enough food is produced globally, but it is not accessible to everyone who needs it. **Food access** refers to the ability to obtain food in ample quantity and of nutritional quality. In the United States, residents of **food deserts** face limited access to nutritious foods, particularly fresh produce (figure $14.1.b$). This problem is compounded when residents do not own a vehicle or have access to public transportation to obtain foods from surrounding areas or lack the funds to do so.

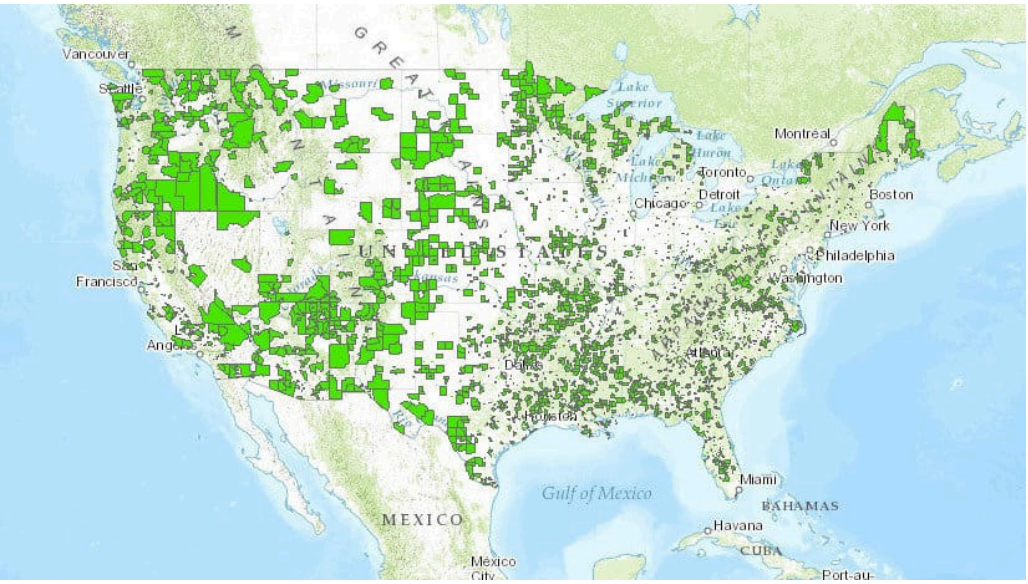

Figure 14.1.b: Food deserts in the contiguous United States are shaded in bright green. Food deserts are distributed over the United States. Examples of large food deserts are in southeastern Oregon and northeastern Arizona. Image by Economic Research Services, USDA (public domain).

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, which differ by gender, age, and life phase (for example, pregnancy), 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.

Food insecurity can result in **undernourishment** and **malnutrition** (a lack of essential nutrients; figure 14.1.c). The economic costs of undernourishment and malnutrition are substantial, potentially costing individuals 10% of their lifetime earnings and costing nations 2-3% of gross domestic product (GDP) in the worst-affected countries (Alderman 2005). This in part due to the reduced ability of under- and malnourished individuals to work. Additionally, without proper nutrition, children can develop disabilities that make it more difficult for them to join to workforce as adults. The economic costs reported here do not even account for the healthcare costs associated with under- and malnutrition.

Figure 14.1.c: A goiter is an enlarged thyroid gland that can result from deficiency of iodine, an essential nutrient. Iodized salt, commonly used in the United States, is one strategy to prevent iodine deficiencies. Image by Almazi/OpenStax (CC-BY). Access for free at openstax.org.

Obesity

Obesity means having excess body fat resulting in a body mass index (BMI) of 30 or higher, and **overweight** individuals have a BMI of 25 or higher (figure $14.1.d$). BMI is a common metric for obesity because it is determined based on weight and height; however, an individual with a big bone structure and/or high muscle mass could have a high BMI without facing the health risks associated with obesity. Likewise, an individual with excess body fat but little muscle mass might have a "healthy" BMI, but their excess body fat could still compromise their health. For these reasons, some experts rely on other metrics, such as relative fat mass (RFM). Relative fat mass is equal to height divided by waist circumference multiplied by 76 for females or 64 for males. An RFM of 32% or higher for females and 25% or higher for males is considered obese. Harvard Chan School of Public Health provides a thorough discussion of the advantages and disadvantages of various obesity metrics.

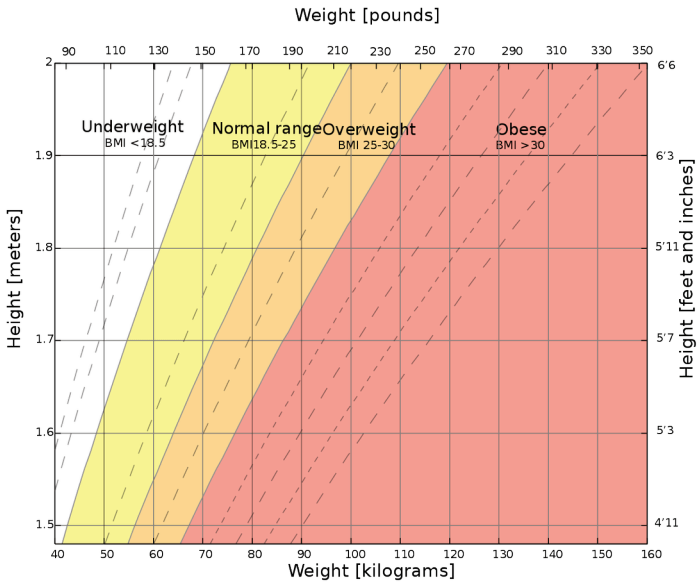

Figure $14.1.d$: This graph shows BMI categories based on height and weight. Height in feet and inches is on the right axis, and weight in pounds is on the top axis. There are four BMI categories: underweight (< 18.5), normal (18.5-25), overweight (25-30), and obese (> 30). BMI is calculated as mass divided by height squared (kg/m^2). Image by InvictaHOG (public domain).

Obesity has become a significant global health challenge, yet is preventable and reversible. Since the 1970s, obesity rates have rapidly increased, resulting in a global obesity epidemic. Thirty-nine percent of the world's adults, or 1.9 billion people, are overweight in 2016. Of these, 650 million are obese (Obesity and Overweight). Obesity was linked to 4.7 million premature deaths in 2017 (about 8% of all deaths that year; Hannah/Our World in Data). The economic cost of obesity has been estimated at $2 trillion (Tremmel et al.).

Initially centered in developed countries, the obesity epidemic now affects countries of all economic statuses. In low-income countries, this results in a triple burden of undernourishment, malnutrition, and 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 $14.1.e$).

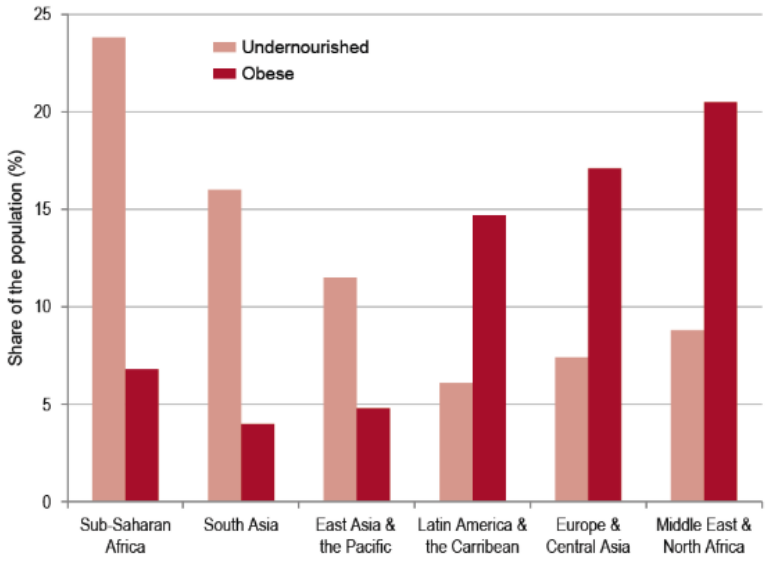

Figure 14.1.e: Obesity (red bars on the right) and undernourishment (pink bars on the left) by region. The share of the population (%) that is undernourished is approximately 24% in Sub-Saharan Africa while approximately 7% of the population in this region is obese. For South Asia 16% of the population is undernourished, and 4% is obese. These percentages 11% and 5% for East Asia and the Pacific, 5% and 15% for Latin America and the Caribbean, 7% and 17% for Europe and Central Asia, and 9% and 20% for the Middle East and North Africa, respectively.

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. 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.

Supplemental Reading

The United Nations explains global food supply and strategies for addressing world hunger here using a variety of informational graphics and videos.

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14.2: Industrial Agriculture

Also known as conventional agriculture, **industrial agriculture** is a method of farming that involves use of synthetic fertilizer, synthetic pesticides, and machinery. Industrial agriculture is dependent on large investments in mechanized equipment powered mostly by fossil fuels. In the case of livestock, most production comes from systems where animals are highly concentrated and confined.

Synthetic Pesticides

Pests are organisms that occur where they are not wanted or that cause damage to crops, humans or other animals (figure $14.2.a$). Thus, the term "pest" is a highly subjective term. A **pesticide** is a term for any substance intended for preventing, destroying, repelling, or mitigating any pest. Though often misunderstood to refer only to insecticides, the term pesticide also applies to **herbicides** (weed killers), fungicides, and various other substances used to control pests. Chemical pesticides can be effective, fast acting, adaptable to all crops and situations. When first applied, pesticides can result in impressive production gains of crops. However, despite these initial gains, excessive use of pesticides can be ecologically unsound (see Disadvantages of Industrial Agriculture). By their very nature, most pesticides create some risk of harm—pesticides can cause harm to humans, animals, and/or the environment because they are designed to kill or otherwise adversely affect living things. At the same time, pesticides are useful to society because they can kill potential disease-causing organisms and control insects, weeds, worms, and fungi.

Figure $14.2.a$: The cotton boll weevil is considered a major pest because of the damage it does to cotton plants. Image by ARS USDA (public domain).

Monoculture Farming

Industrial agriculture employs **monoculture** farming, which involves growing only one species of crop in a large area (figure $14.2.b$). The plants in a monoculture are evenly spaced and have the same planting, irrigation, fertilizer, harvesting, etc. requirements, and this uniformity results in efficient use of farming machinery. Often, the crop is a **high yield variety** (high yielding variety; HYV), which is produced through selectively breeding individual plants with desirable characteristics. Compared to traditional crops, HYVs can produce more per unit area of land. Monoculture farming compromises genetic and species diversity in agriculture, however, promoting the spread of pests and risking that all the plants for hundreds of acres could be susceptible to the same disease (see Genetic Diversity).

Figure 14.2.b: Monocultures like this potato farm (left) and cotton farm (right) make it easier to use farming equipment; however, this reduces genetic diversity and consumes fossil fuels. Left image by NightThree (CC-BY) and right image by Kimberly Vardeman (CC-BY).

Advantages of Industrial Agriculture

Industrial agriculture has delivered tremendous gains in productivity and efficiency. Food production worldwide has overall risen since the 1940s (figure 14.2.c); the World Bank estimates that between 70 percent and 90 percent of the recent increases in food production are the result of industrial agriculture rather than greater acreage under cultivation (figure 14.2.d). United States consumers have come to expect abundant and inexpensive food. Additionally, the use of synthetic pesticides ensures that produce is relatively free of blemishes (figure 14.2.e).

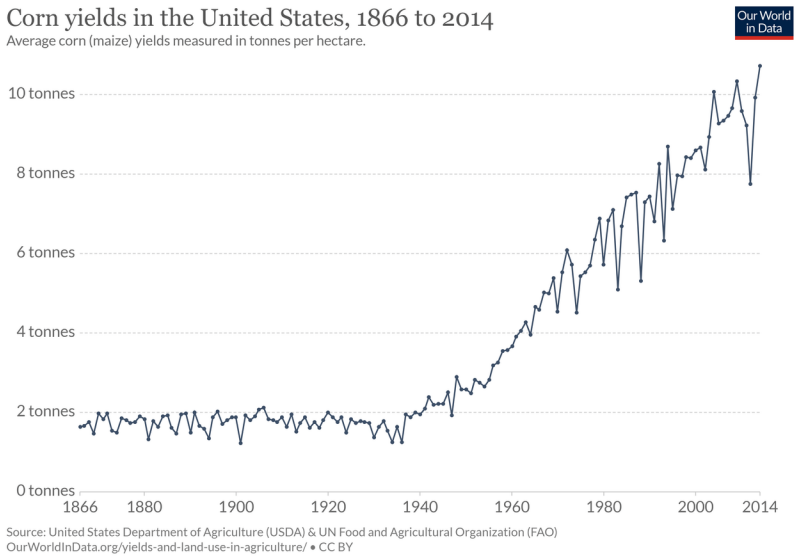

Figure 14.2.c: Corn yields in metric tons (tonnes; 1000 kilograms) per hectare over time. While yields have fluctuated from year to year, they have overall increased since the 1940s. This improving agricultural efficiency is partly due to industrial agricultural practices. Image by Hannah Ritchie and Max Roser/Our World in Data (CC-BY).

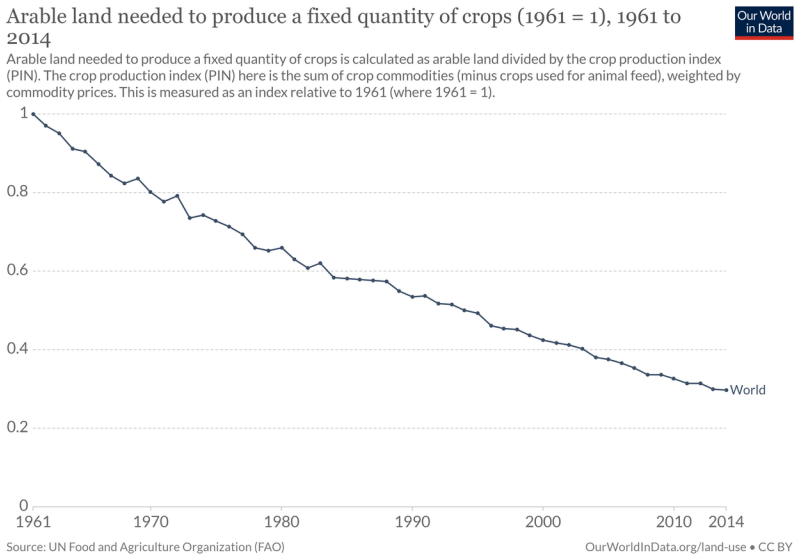

Figure 14.2.d**:** The arable (farmable) land required to produce a fixed amount of a crop has decreased over time due to improved agricultural efficiency. Image by Hannah Ritchie and Max Roser/Our World in Data (CC-BY).

Figure $14.2.e$: Many of us carefully inspect produce at the grocery store and select those without blemishes. This visually appealing produce results from synthetic pesticides use. Image by Amanda Mills (public domain).

Industrial agriculture expands where crops can be cultivated. Applying synthetic fertilizers to poor soils can make them fertile. Additionally, irrigation systems promote high agricultural productivity in regions and during seasons that would otherwise only support the most drought-tolerant species. For example, about 25% of the food consumed in the United States is produced in California's Central Valley, which receives little rain in the summer months (figure $14.2.f$).

Figure $14.2.f$: The four regions of California's Central Valley from north to south are the Sacramento Valley, Delta and Eastside Streams, San Joaquin Basin, and Tulare Basin. Image by USGS (public domain).

Disadvantages of Industrial Agriculture

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

Economic pressures have led to a tremendous loss to the number of farms, particularly small farms, and farmers during the past

few decades. More than 155,000 farms were lost from 1987 to 1997. Economically, it is very difficult for potential farmers to enter the business today because of the high cost of doing business. Farming equipment is expensive, and the industrial agricultural system favors large corporate farms, which can more easily invest in this equipment. While this equipment promotes efficiency, it also reduces the number of jobs in agriculture (figure $14.2.g$).

Figure $14.2.g$: The number of people working in agriculture in selected countries over time (from 1801-2015). Generally, the number of agricultural workers has declined as farming practices increased in efficiency and as farming machinery completed tasks that were once manual. This is both an advantage because people are free to pursue other careers and a disadvantage because of the reduction in jobs. In Japan, the number of agricultural workers peaked above 16 million around 1900 and again around 1960. In the United States, it peaked to nearly 12 million around 1900. France followed a similar pattern, peaking around 1925 at approximately 9 million workers. There were over 6 million agricultural workers in South Korea in 1950, and this has overall declined (although there was a spike around 1980). In Spain the number of workers was over 5 million in 1950 and has since decreased. In the United Kingdom, the number of agricultural workers peaked around 1960 at about 3.5 million. The other countries shown (Netherlands, Finland, Sweden, and Belgium) have consistently had under 1 million agricultural workers. Image by Max Roser/Our World in Data (CC-BY).

The mechanical farming equipment required for industrial agriculture relies on fossil fuels. Burning fossil fuels releases air pollution, including greenhouse gases, which cause climate change. Additionally, the synthetic fertilizers and pesticides used in industrial agriculture are produced from fossil fuels. Furthermore, agriculture areas rarely contain as much biomass (organic matter that comprises living things) as biodiverse, intact ecosystems. Biomass is an important carbon sink because its organic molecules store carbon that could otherwise be in the atmosphere as carbon dioxide or methane, both greenhouse gases. Soils with a substantial organic component are also carbon sinks. Industrial agricultural practices that deplete these soils (see below) contribute to climate change, but alternative practices can promote this benefit of healthy soils (see Sustainable Agriculture).

While synthetic fertilizers provide crops with the necessary nutrients for high productivity, excess nutrients from fertilizers can enter bodies of water through runoff. This can lead to a bloom of algae or photosynthetic bacteria in lakes, rivers, and bays in a process called **eutrophication**. These photosynthetic microorganisms sometimes produce toxins that kill aquatic animals and can even harm the humans who consume these animals. Furthermore, they block aquatic plants from accessing light. Eventual decomposition of algal blooms requires oxygen, which results in **hypoxia** (low levels of dissolved oxygen), further harming aquatic species. Additionally, industrial agriculture pollutes water with pesticides and sediments. Pesticides are not only widespread in surface waters, but pesticides from every chemical class have been detected in groundwater.

Industrial agricultural practices often deplete soil quality. For example, wind and water erosion of exposed topsoil removes particles and nutrients from the soil (which also contributes to eutrophication and sediment pollution). Tilling (mixing the soil) and overgrazing of livestock exacerbates erosion. When livestock remove too much vegetation from an area, plant roots no longer anchor the soil in place, and erosion ensues. Farming equipment compacts the soil. This limits infiltration of water into the soil (decreases soil permeability), makes it more difficult for roots to penetrate the soil, and hinders gas exchange in roots. In extreme cases, soil has eroded and lost its ability to retain water that once arable (farmable) land becomes a desert-like (**desertification**; see Soil Degradation; figure $14.2.h$).

Figure 14.2.h: Overgrazing depleted the soil in the Rukwa Plains of southwestern Tanzania. Image by Lichinga (CC-BY-SA).

Irrigation can lead to **salinization** (increased salinity). While the water itself eventually evaporates, is transpired, or drains from the soil, the minerals dissolved in the water may remain in the soil. Over time, these minerals can accumulate to levels that are toxic for most plants. As discussed in Water Usage, irrigation for agriculture accounts for 69% of global water usage. Withdrawal of sufficient water for irrigation contributes to water shortages and diverts water from ecosystems (see Aqueducts).

Repeated pesticide application exerts selective pressure on insects, fungi, and other crop pests to evolve pesticide resistance. By chance, some individuals in a pest population may carry gene versions that confer pesticide resistance. When these populations are exposed to pesticides, individuals with these gene versions are the most likely to survive and reproduce. They then pass these genes to their offspring, and pesticide resistance becomes more and more common in the population over time (figure 14.2.i). At this point, pesticides may need to be applied at greater concentrations or more frequently to achieve the same effect. If pesticide that was initially used is no longer effective at all, the farmer would be forced to find a different pesticide. Over 400 insects and mite pests and more than 70 fungal pathogens have become resistant to one or more pesticides.

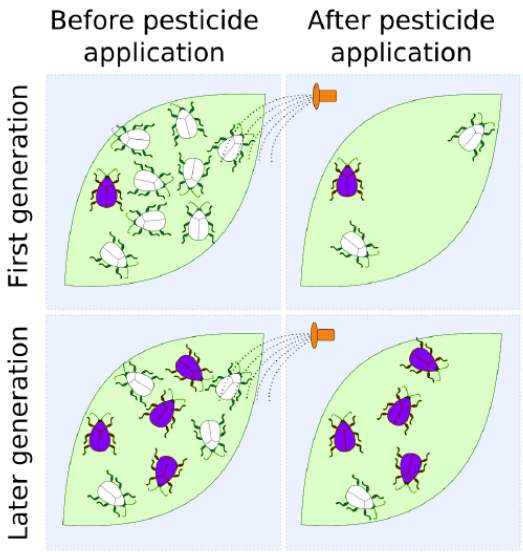

Figure 14.2.i: Pesticide application can exert selection for the evolution of pesticide resistance. In this hypothetical example, the purple beetle has a gene version that makes it resistant to pesticides (upper left). Pesticides are applied, killing most of the susceptible individuals (white beetles; upper right). In a later generation, purple, resistant beetles are more common because they had a better chance of surviving and reproducing (lower left). Upon another pesticide application, an even greater proportion of the population is resistant. Image modified from Delldot (CC-BY-SA).

The human health and environmental costs of pesticide use have been unevenly distributed. Despite the fact that the lion's share of chemical pesticides are applied in developed countries, 99 percent of all pesticide poisoning cases occur in developing countries where regulatory, health and education systems are weakest. Many farmers in developing countries overuse pesticides and do not take proper safety precautions because they do not understand the risks and fear smaller harvests. Making matters worse, developing countries seldom have strong regulatory systems for dangerous chemicals; pesticides banned or restricted in industrialized countries are used widely in developing countries. Farmers' perceptions of appropriate pesticide use vary by setting and culture. Prolonged exposure to pesticides has been associated with several chronic and acute health effects like non-Hodgkin's lymphoma, leukemia, as well as cardiopulmonary disorders, neurological and hematological symptoms, and skin diseases.

Pesticides have also placed stresses on pollinators and other beneficial insect species. They can lead to the destruction of natural enemies, which would regulate pest populations in an intact ecosystem. For example, once apple growers began controlling pests with the pesticide dichlorodiphenyltrichloroethane (DDT), which has since been banned, they quickly found their orchards being attacked by scale insects and mites. The reason: DDT had killed off their natural enemies. More generally, pollution from industrial agriculture along with habitat loss due to converting healthy ecosystems into agricultural fields is a major threat to biodiversity. As mentioned previously, monoculture farming limits biodiversity in crops.

With respect to animal agriculture, keeping livestock are kept in close quarters increases the risk of disease spread among them. For these reason, food animals are commonly given antibiotics, either preventatively or to treat existing infections. As discussed in the Infectious Diseases section, the overuse of antibiotics (whether in humans or farm animals) increases selection for the evolution of antibiotic-resistant strains of bacteria or other disease-causing organisms. Infections by antibiotic-resistant strains are more difficult to treat.

As with many industrial practices, potential health hazards are often tied to farming practices. Under research and investigation currently is the sub-therapeutic use of antibiotics in animal production, and pesticide and nitrate contamination of water and food. Farm worker health is also a consideration in all farming practices.

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- Insecticides from *Biology* by John W. Kimball (licensed under CC-BY)
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14.3: Selective Breeding and Genetic Engineering

The development of a new crop variety 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.

Selective Breeding (Artificial Selection)

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** (artificial selection), human-facilitated reproduction of individuals with desirable traits. For example, high yield varieties were produced through selective breeding. 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.

Selective breeding is limited, however, by the life cycle of the plant and the genetic variants that are naturally present. For example, even the fastest flowering corn variety has a generation time of 60 days (the time required for a seed to germinate, produce a mature plant, get pollinated, and ultimately produce more seeds) in perfect conditions. Each generation provides an opportunity to selectively breed individual plants and generate seeds that are slightly closer to the desired outcome (for example, producing bigger, juicier kernels). Furthermore, if no individuals happen to possess gene variants that result in bigger, juicier kernels, it is not possible to artificially select this trait. Finally, traditional breeding shuffles all of the genes between the two individuals 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.

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 (figure $14.3.a$). In doing so, they permanently (and unknowingly) altered its genetic instructions.

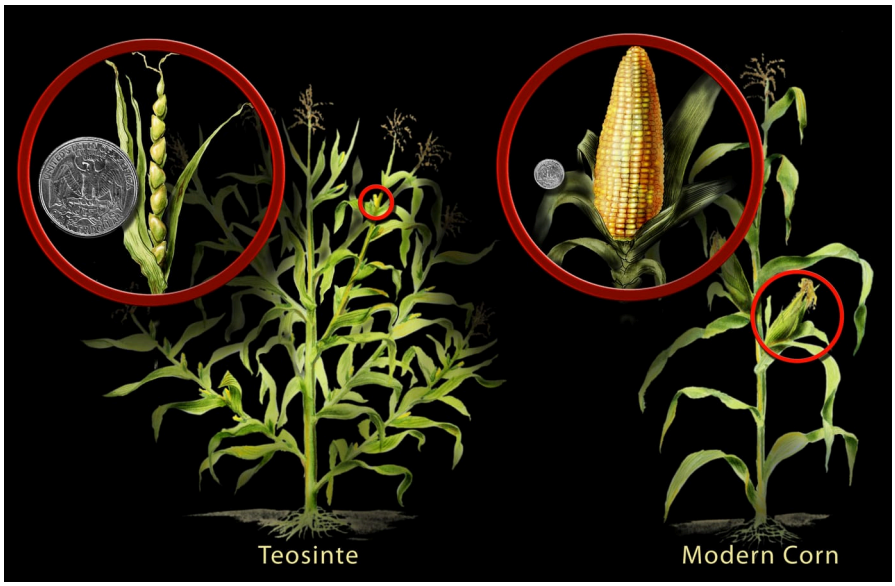

Figure $14.3.a$: A wild grass called teosinte was genetically modified through selective breeding to produce what is now known as maize (corn). This process of transformation started thousands of years ago by indigenous people of what is now Mexico. Image by Nicolle Rager Fuller/ National Science Foundation (public domain).

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 $14.3.b$). 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 14.3.b: *Brassica oleracea* is a plant in the mustard family and is known as wild cabbage. From it were developed many familiar crops, such as cauliflower, broccoli, Brussel sprouts, and of course, cabbage. Image by Kulac (CC-BY-SA).

Genetic Engineering

Genetic engineering is the process of directly altering an organism's DNA to produce the desired crops more rapidly than selective breeding. Because genes can be obtained from other species or even synthesized in the lab, scientists are not limited by existing genetic variation within a crop species (or closely related species with which they can be crossed). This broadens the possible traits that can be added to crops. Modern genetic engineering is more precise than selective breeding 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 (figure 14.3.c).

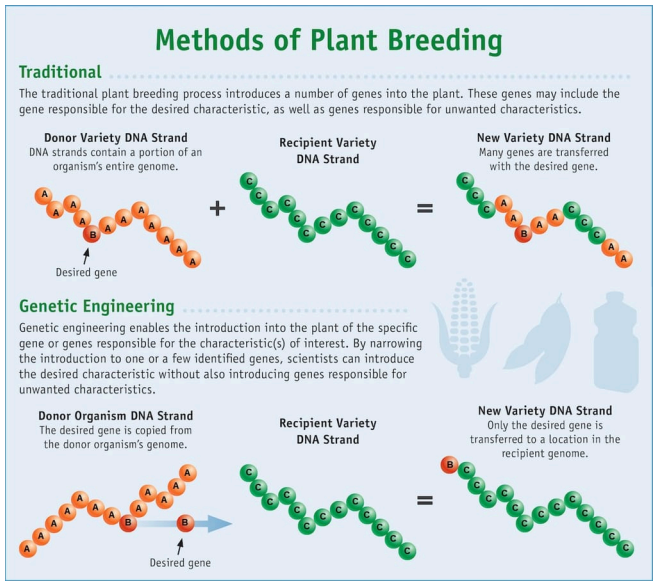

Figure $14.3.c$: Both selective (traditional) breeding and modern genetic engineering produce genetic modifications. Genetic engineering allows for fewer and more precise genetic modifications. The traditional plant breeding process introduces a number of genes into the plant. These genes may include the gene responsible for the desired characteristic, as well as genes responsible for unwanted characteristics. In traditional breeding, the donor variety DNA strand (A) and recipient variety DNA strand (C) are combined to produce the new variety DNA strand. The donor DNA strand contains a portion of an organism's entire genome, including the desired gene (B). In the new variety DNA strand, many genes are transferred with the desired gene. Genetic engineering enables the introduction into the plant of the specific gene or genes responsible for the characteristics of interest. By narrowing the introduction to one of a few identified genes, scientists can introduce the desired characteristic without also introducing genes responsible for unwanted characteristics. In genetic engineering, the desired gene (B) is copied from the donor organism's genome (A). The desired gene from the donor organism DNA strand and the recipient variety DNA strand (C) are combined to produce the new variety DNA strand. Only the desired gene is transferred to a location in the recipient genome. Modified from Michael J. Ermarth/FDA (public domain).

Genetically modified organisms (**GMOs**) are those that have had their DNA altered through genetic engineering. Genetically modified crops are sometimes called genetically engineered (GE) crops. **Transgenic organisms** are a type of genetically modified organism that contains genes from a different species. Because they contain unique combinations of genes and are not restricted to the laboratory, transgenic plants and other GMOs are closely monitored by government agencies to ensure that they are fit for human consumption and do not endanger other plant and animal life. Because these foreign genes (transgenes) can spread to other species in the environment, particularly in the pollen and seeds of plants, extensive testing is required to ensure ecological stability.

How to Genetically Modify Plant Cells

DNA can be inserted into plant cells through various techniques. For example, a **gene gun** propels DNA bound to gold particles into plant cells. (DNA is negatively charge and clings to positively charged gold.) A more traditional approach employs the plant pathogen ***Agrobacterium tumefaciens*** (figure $14.3.d$). Ordinarily, this bacterium causes crown gall disease in plants by inserting a circular piece of DNA, called the **Ti plasmid**, into plant cells. This DNA incorporates into plant chromosomes, giving them genes to produce the gall (figure $14.3.e$), which provides a home for the bacterial pathogen.

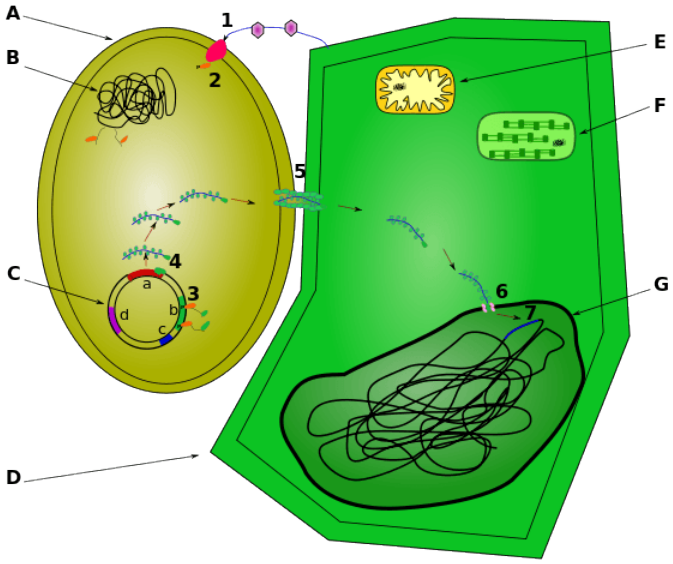

Figure $14.3.d$: An *Agrobacterium tumefaciens* cell (A) inserts the Ti plasmid (C), which contains T-DNA (a) into a plant cell (D). The T-DNA eventually enters the plant nucleus (G), where the plant DNA is stored. Image by Chandres (CC-BY-SA).

Figure $14.3.e$: A crown gall caused by *Agrobacterium tumefaciens*. This bacterium inserts DNA into plant cells, which causes them to produce the crown gall. This process can be adjusted by scientists to insert genes that code for desirable traits into crop species. Image by Scott Nelson (public domain).

Scientists alters the process by which *Agrobacterium* infects and genetically alter plant cells to produce genetically modified plants with agriculturally beneficial traits as follows (figure $14.3.f$):

1. T-DNA, which codes for the crown gall is removed from the Ti plasmid, and genes for desired traits are added.
2. The modified plasmid is then added back to *Agrobacterium*.
3. *Agrobacterium* infects undifferentiated plant cells (stem cells that can develop into any part of the plant; figure $14.3.g$).
4. The modified plant cells are given hormones to produce the entire plant.

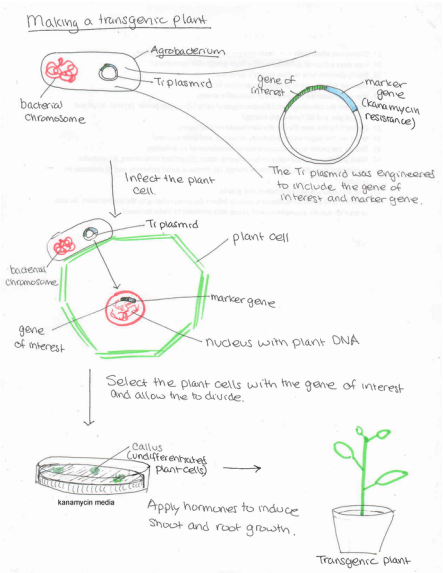

Figure 14.3.f: The process of producing a transgenic plant using *Agrobacterium*. The Ti plasmid was engineered to include the gene of interest and marker gene, which will later indicate which cells are transgenic. A rectangle represents *Agrobacterium*. It contains regular bacterial DNA and the Ti plasmid, represented by a circle. The T-DNA (which provides instructors for producing a crown gall) is removed, and a transgene (gene of interest) and maker gene are inserted instead. The gene of interest is colored green, and the marker gene (for resistance to the antibiotic kanamycin) is colored blue. Next, plant cells are infected with *Agrobacterium*. The bacterial cell inserts the Ti plasmid into a polyhedral plant cell. The transgene is transferred to the plant cell nucleus, which contains regular plant DNA. Next, the plant cells with the gene of interest are selected and allowed them to divide. This is done by culturing the plant cells on kanamycin media in a petri dish. Calluses, clusters of undifferentiated plant cells, are produced. Finally, hormones are applied to induce shoot and root growth. An arrow points from the petri dish to a potted transgenic plant. Image by Melissa Ha (CC-BY).

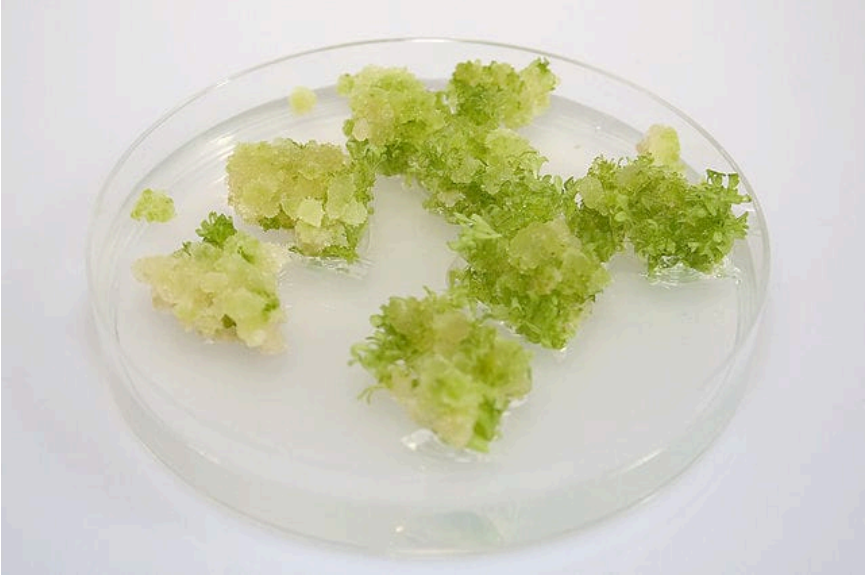

Figure 14.3.g: Individual plant cells are first genetically engineered with *Agrobacterium*. They then grow into **calluses** (blobs of undifferentiated plant cells) and are given hormones to induce root and shoot development. Because all the cells in the plant that eventually grows descended from a single genetically engineered cell, the entire plant is transgenic. Image by Igge (CC-BY-SA).

Examples of Genetically Modified Crops

Many genetically modified crops have been approved in the U.S. and produce our foods. The first genetically modified organism approved by the U.S. Food and Drug Administration (FDA) in 1994 was **Flavr Savr™ tomatoes**, which have a longer shelf life (delayed rotting) because a gene responsible for breaking down cells in inhibited. Flavr Savr tomatoes are genetically modified (because their DNA has been altered) but not trasgenic (because they do not contain genes from another species). The Flavr Savr tomato did not successfully stay in the market because of problems maintaining and shipping the crop. **Golden rice** produces β-

carotene, a precursor to vitamin A (figure $14.3.h$; β-carotene is also in high concentrations in carrots, sweet potatoes, and cantaloupe, giving them their orange color.) **Roundup Ready®** corn, cotton, and soybeans are resistant to this common herbicide, making it easier to uniformly spray it in a field to kill the weeds without harming the crops (figure $14.3.i$).

Figure $14.3.h$: Golden rice has an orange-yellow color because it contains up to 35 μg β-carotene (a precursor to vitamin A) per gram of rice, which could prevent millions of cases of blindness worldwide. Image by International Rice Research Institute (CC-BY).

Figure $14.3.i$: Roundup is a common herbicide. Roundup Ready® plants are genetically modified to resist roundup, meaning the herbicide does not kill them. This allows farmers to uniformly spray Roundup, killing weeds without harming the crops. Image by Mike Mozart (CC-BY).

Crops have also been engineered to produce insecticides. *Bacillus thuringiensis* (Bt) is a bacterium that produces protein crystals that are toxic to many insect species that feed on plants. Insects that have eaten Bt toxin stop feeding on the plants within a few hours. After the toxin is activated in the intestines of the insects, death occurs within a couple of days. The gene to produce **Bt toxin** has been added to many crops including corn (figure $14.3.j$), potatoes, and cotton, providing plants with defense against insects.

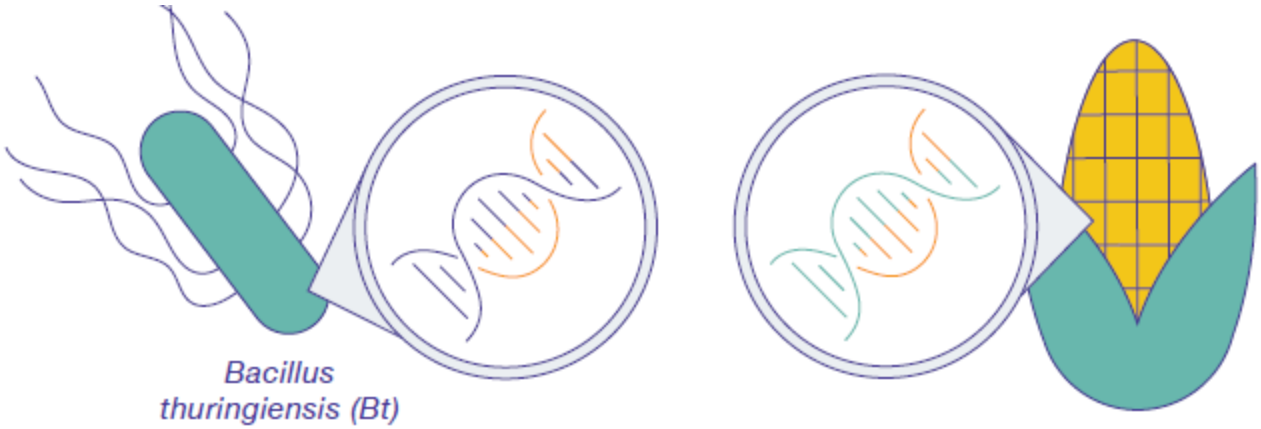

Figure $14.3.j$: Genetic engineering to produce Bt corn. The gene from *Bacillus thuringiensis* that produces Bt toxin is removed and inserted into the corn plant. The Bt corn now produces the insecticide (Bt toxin) and can defend itself against pests. Image by FDA (public domain).

Genetically modified foods are widespread in the United States. For example, 94% of soy crops were genetically modified for herbicide resistance in 2020. Likewise, 8% of cotton and 10% of corn crops were modified for herbicide resistance in addition to the 83% of cotton and 79% of corn crops that were genetically modified in multiple ways.

Genetically modified animals have recently entered the market as well. **AquaAdvantage® salmon** are modified to grow more rapidly and were approved in November of 2015. However, as of March 2021, they have still not been sold due to legal challenges. In 2020, the FDA approved **GalSafe™ pigs** for medicine and food production. These pigs lack a molecule on the outside of their cells that cause allergies in some people.

Advantages of Genetically Modified Crops

Advances in biotechnology may provide consumers with foods that are nutritionally-enriched, longer-lasting, or that contain lower levels of certain naturally occurring toxins present in some food plants. For example, researchers are using biotechnology to try to reduce saturated fats in cooking oils and reduce allergens in foods. Whether these benefits will reach the people who need them most remains to be seen. While cultivating golden rice could address vitamin A deficiency in millions of people, it has not historically been accessible to these people because it is patented and expensive. Similarly, genetically modified seeds could increase the income of impoverished farmers if they were available at low or no cost, but this is not always the case.

Rainbow and SunUp papayas are a success story of how genetically modified crops can benefit small farmers and the economy in general. In the early 1990s, an emerging disease was destroying Hawaii's production of papaya and threatening to decimate the $11-million industry (figure $14.3.k$). Fortunately, a man named Dennis Gonsalves (figure $14.3.l$), 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's seeds.

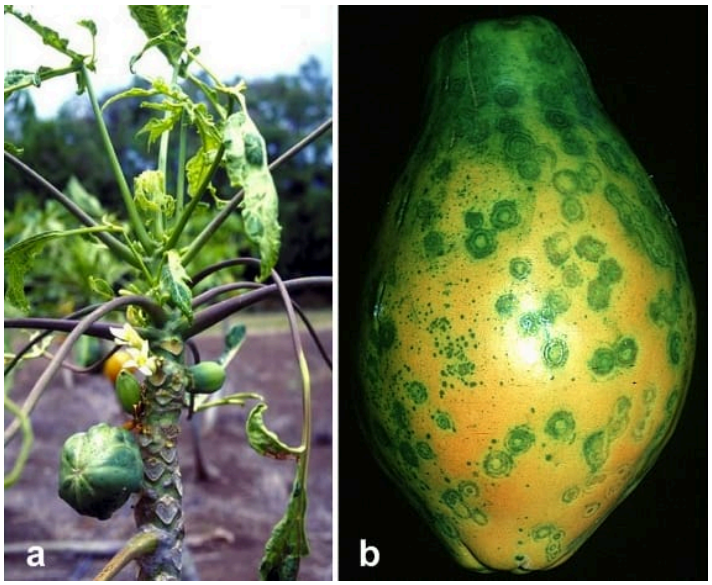

Figure $14.3.k$: The symptoms of papaya ringspot virus are shown on the tree (a) and fruit (b). Image by APS (public domain).

Figure $14.3.l$: Dennis Gonsalves genetically engineered papayas to resist the ringspot virus. Image by ARS USDA (public domain).

The effect of genetically modified crops on the environment depends on the specific genetic modification and which agricultural practices it promotes. For example, Bt crops produce their own insecticides such that external application of these chemicals is unnecessary, reducing the negative impacts of industrial agriculture. Ongoing research is exploring whether crops can be engineered to fix nitrogen in the atmosphere (as some bacteria do) rather than relying on ammonium, nitrites, and nitrates in the soil. If these crops were successfully engineered, they could reduce synthetic fertilizer application and minimize nutrient runoff that leads to eutrophication.

Genetically modified crops may have the potential to conserve natural resources, enable animals to more effectively use nutrients present in feed, and help meet the increasing world food and land demands. In practice, however, countries that use genetically modified crops compared to those that do not only enjoy a slight (or nonexistent) increase in yield.

Disadvantages of Genetically Modified Crops

Social Concerns

Intellectual property rights are one of the important factors in the current debate on genetically modified crops. Genetically modified crops can be patented by agribusinesses, 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 (figure $14.3.m$).

Figure $14.3.m$: Protesters in Washington D.C. oppose genetically modified organisms and Monsanto specifically. Image cropped from Sarah Stierch (CC-BY).

Environmental Concerns

Genetically modified crops present several environmental concerns. Monoculture farming already reduces biodiversity, and cultivating genetically modified crops, for which individual plants are quite similar genetically, exacerbates this. The use of Roundup Ready® crops naturally encourages widespread herbicide use, which could unintentionally kill nearby native plants. This practice would also increase herbicide residues on produce. While Bt crops are beneficial in the sense that they do not require external insecticide application, but Bt toxin is spread in their pollen. An early study found that Bt corn pollen may be harmful to monarch caterpillars (figure $14.3.n$), but only at concentrations that are seldom reached in nature. Follow-up studies found that most of Bt corn grown did not harm monarchs; however, the one strain of Bt corn did was consequently removed from the market.

Figure $14.3.n$: An early study suggested that pollen containing Bt toxin can harm beneficial and native insects, like this monarch caterpillar. However, without Bt crops, farmers are more likely to spray insecticides, circulating more harmful chemicals than pollen from Bt crops does. Image by Judy Gallagher (CC-BY).

Through interbreeding, or hybridization, genetically modified crops might share their transgenes 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 genetically modified crop to a wild relative, it might transform the wild species into a **superweed** – 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.

Not only could escaped genes alter weedy species, but they could also enter populations of native species. This could make some native species better competitors than they were previously, disrupting ecosystem dynamics. (They could potentially outcompete other native species with which they would otherwise coexist.)

While there is evidence of genetic transfer between genetically modified crops and wild relatives, there is not yet evidence of ecological harm from that transfer. Clearly, continued monitoring, especially for newly-developed crops, is warranted.

The escape of genetically modified animals has potential to disrupt ecosystems as well. For example, if AquaAdvantage salmon were to escape into natural ecosystem, as farmed fish often do, they could outcompete native salmon, including endangered species. Their genetic modification, which facilitates rapid growth, could result in a competitive advantage.

Health Concerns

In addition to environmental risks, some people are concerned about potential health risks of genetically modified 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 changes. Furthermore, selective breeding actually has a larger and more unpredictable impact on a species's genetics because of its comparably crude nature.

To address these concerns (and others), 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 genetically modified crops. The report, titled *Genetically Engineered Crops: Experiences and Prospects*, reviewed more than 900 research articles, in addition to public comments and expert testimony. 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." Additionally, the UN's Food and Agriculture Organization has concluded that risks to human and animal health from the use of GMOs are negligible. The scientific consensus on genetically modified crops is quite clear: they are safe for human consumption.

The potential of genetically modified crops to be allergenic is one of the potential adverse health effects, and it should continue to be studied, especially because some scientific evidence indicates that animals fed genetically modified 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.

Are Genetically Modified Crops the Solution We Need?

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

However, in many cases, the early promises of genetically engineered 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 genetically modified 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 genetically engineered 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 genetically modified crops are developed for only two purposes: to introduce herbicide resistance or pest resistance. Genetically modified crops are concentrated in developed countries, and their availability in developing countries, where they are perhaps most needed,

is limited (figure 14.3.o).

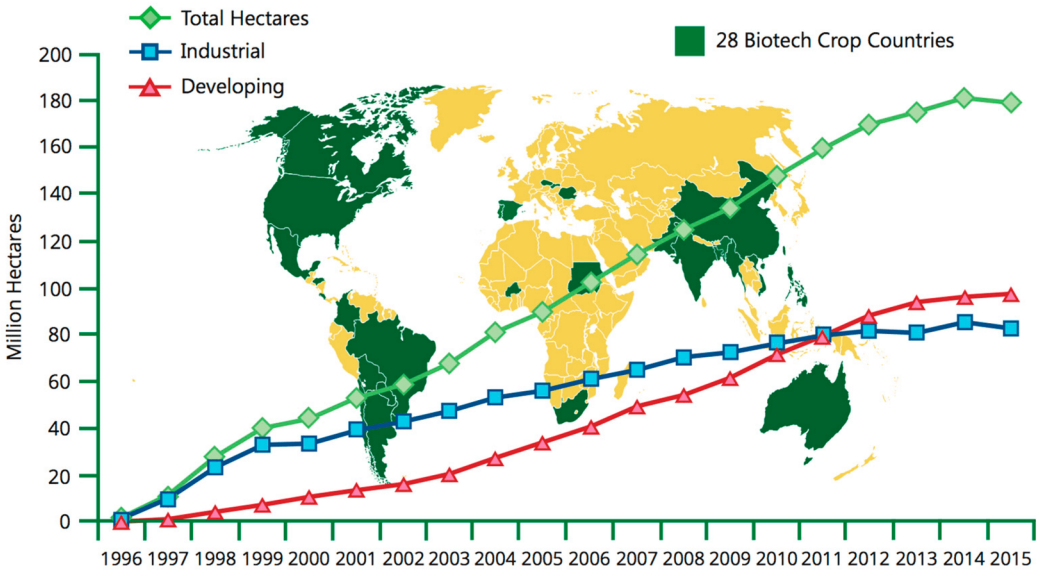

Figure 14.3.o: Global area of genetically modified crops in millions of hectares 1996–2015. Overall, the hectares of genetically modified crops has increased, and in 2011, developing countries surpassed industrial countries. By 2015, out of the 28 countries that grew biotech crops, 20 were developing, and only eight were developed countries. Latin American, African, and Asian farmers together grew 97.1 million hectares (54%) of the global 179.7 million biotech hectares, whereas industrial countries only planted 83 million hectares or 46%. Image and caption (modified) from Taheri, F., Azadi, H., & D'Haese, M. (2017). A World without Hunger: Organic or GM Crops? *Sustainability*, *9*(4), 580. doi:10.3390/su9040580. (CC-BY)

Suggested Supplementary Reading

NASEM. 2016. Genetically Engineered Crops: Experiences and Prospects.

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14.4: Sustainable Agriculture

Sustainable agriculture is a method of farming that does not deplete natural resources or degrade the environment and can therefore be continued indefinitely. Sustainable farms often rely on components of local ecosystems. For example, they might promote conditions for natural decomposition of wastes or employ natural enemies to control pests through predation or competition. More specifically, the 1977 and 1990 “Farm Bills” describe sustainable agriculture as "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;
- enhance the quality of life for farmers and society as a whole."

Promoting biodiversity is key to sustainable agriculture, and high biodiversity results intact ecosystem services such as nutrient cycling and regulation of pest populations. This is consistent with the goal of sustainable agriculture: to mimic the processes found in natural ecosystems. In contrast to the monocultures of industrial agriculture, **polyculture** farming (growing different species together) is a common practice in sustainable agriculture. This assists with regulating pests and maintaining soil fertility (see below). **Seed banks**, locations at which many different types of seeds are stored, are key to conserving the genetic diversity of crops. These storage sites are cold enough to keep seeds frozen naturally (figure $14.4.a$).

Figure $14.4.a$: The Svalbard Global Seed Vault in Norway. Image by Miksu (CC-BY-SA).

Integrated Pest Management

Integrated Pest Management (IPM) refers to a mix of farmer-driven, ecologically-based pest control practices that seek to reduce reliance on synthetic chemical pesticides. It uses several methods simultaneously to control pest populations. The steps of integrated pest management are to (1) identify true pests, (2) set thresholds and monitor (figure $14.4.b$), and (3) develop an action plan. As many insects, microbes, and other organisms found in an agricultural area have a neutral or beneficial effect, it is not necessary to remove them. True pests are those that are causing economic harm, and they are managed (kept below economically damaging levels) rather than eradicated.

Figure 14.4.b: A retired Navy commander and landowner inspect an insect trap as part of an Integrated Pest Management (IPM) conservation practice. Image by NRCS (public domain).

An IPM Action Plan draws on four types of control: cultural, mechanical, biological, and chemical. These methods are listed in order of least to most environmental impact and are thus applied in this order. For example, cultural control is attempted first. If that is not effective, mechanical control is added to the plan, and so on. Chemical control is used as a last resort and is deemphasized in an IPM plan. When pesticides must be used, they are selected and applied 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.

An Alternative to Spraying: Bollworm Control in Shandong

Farmers in Shandong (China) have been using innovative methods to control bollworm infestation in cotton when this insect became resistant to most pesticides. Among the control measures implemented were:

1. The use of pest resistant cultivars and interplanting of cotton with wheat or maize.
2. Use of lamps and poplar twigs to trap and kill adults to lessen the number of adults.
3. If pesticides were used, they were applied on parts of the cotton plant's stem rather than by spraying the whole field (to protect natural enemies of the bollworm).

These and some additional biological control tools have been effective in controlling insect populations and insect resistance, protecting surroundings and lowering costs.

Cultural Control

Cultural control refers to minimizing the conditions that allow pests to thrive and spread. Examples include alternating which crops are planted each year (**crop rotation**), planting multiple types of crops near each other (**intercropping**; figure 14.4.c), selecting pest-resistant varieties, and planting pest-free rootstock (underground plant parts). Crop rotation prevents pests that are specialized to a particular type of crop from continuing year after year because their host plants are only available in certain years. Similarly, intercropping spatially limits the spread of pests. **Strip cropping** is a type of intercropping that involves growing different types of crops in alternating rows. Pests may infest one (or several) rows of their host species, but they would have to move past multiple rows of non-hosts to access additional host plants. Additionally, cultural control can involve optimizing irrigation and fertilizer application to promote plant defense and limit disease spread. Cultural control methods can be very effective and cost-efficient and present little to no risk to people or the environment.

Figure 14.4.c: *Momordica charantia* (bitter melon) intercropped with rice in the Philippines (cultural control). Bitter melon plants emerge from holes in plastic, which is used for mechanical control of weeds. Image by Judgefloro (CC-BY-SA).

Mechanical Control

Mechanical control refers to physically removing pests or excluding them with barriers (figure 14.4.d). Mechanical controls that remove pests include sticky insect traps, mole traps, and removing weeds by hand. Netting to exclude birds, deer fencing, and weed cloth, plastic weed barriers (figure 14.4.c) or mulch are additional examples of mechanical control.

Figure 14.4.d: This solar insect trap is an example of mechanical control. It emits ultraviolet light to attract insects and is recharged using small solar panels. Image by MGK Solar Trap (CC-BY-SA).

Biological Control

Biological control is the use of organisms to reduce pest populations (also see Invasive Species). One biological control strategy involves releasing natural enemies, such as predators, parasites, or parasitoids of the pest organisms (parasitoids are similar to parasites, but they consistently kill their hosts). Home gardeners can also rely on natural enemies by purchasing preying mantises, ladybugs (ladybird beetles), or lacewings for release (figure 14.4.e). Successful examples include ladybird beetles to depress aphid populations, parasitoid wasps to control whiteflies, and fungi, such as *Trichoderma*, to suppress fungal-caused plant diseases.

Figure 14.4.e: Lacewings are natural predators of garden and crop pests. Image by artsehn/Pixabay (Pixabay license).

If not used carefully, chemical control can have unintended negative consequences for biological control. In 1887, the cottony cushion scale (native to Australia) was devastating the citrus groves of California. A U.S. entomologist went to Australia to find a natural enemy and came back with the **vedalia beetle**, a species of ladybird beetle. Released in California, the beetle quickly brought the scale under control, at least until 1946. In that year, the pest made a dramatic comeback. This coincided with the first use of the now-banned pesticide dichlorodiphenyltrichloroethane (DDT) in the groves. Not only did DDT kill the target pest insects, but it killed the vedalia beetle as well. Only by altering spray procedures and reintroducing the beetle was the scale insect again controlled.

Another strategy for biological control involves releasing sterile males, which compete with fertile males for mates, ultimately decreasing pest population size. This technique was first applied against the screwworm fly, a serious pest of cattle (figure 14.4.f). The female flies lay their eggs in sores or other open wounds on the animals. After hatching, the larvae eat the tissues of their host. As they do so, they expose a still larger area to egg laying, often finally killing the host.

Figure 14.4.f: Thought to be eradicated in the United States by 1966, the screwworm fly, a cattle pest, reemerged in deer at Key Deer National Refuge in Florida in 2016. Sterile males were again released, and the pest was eradicated from Florida in 2017. Image by Judy Gallagher (CC-BY).

Prior to its eradication from the southeastern United States, the screwworm was causing huge annual livestock losses. The sterile male technique involves releasing factory-reared and sterilized flies into the natural population. Sterilization is done by exposing

the factory flies to just enough gamma radiation to make them sterile but not enough to reduce their general vigor.

Starting in early 1958, up to 50 million sterilized flies were released each week from aircraft flying over Florida and parts of the adjoining states. Each time a fertile female in the natural population mated with a sterile male, the female layed sterile eggs. Since the females mate only once, her reproductive career was at an end. By early 1959, the pest was totally eliminated east of the Mississippi River. The problem in southwestern states was more challenging because the fly winters in Mexico and could move across the border with each new season. Even so, by expanding the program to include Mexico as well, the screwworm fly was finally eliminated from Mexico in 1991.

The sterile male technique also successfully controlled the Mediterranean fruit fly ("medfly"), a destructive fruit fly of citrus, peaches, pears, and apples in California.

Chemical Control

Chemical control refers to the use of pesticides. If chemical control is needed, IPM favors highly targeted chemicals, such as pheromones to disrupt pest mating. **Pheromones** are chemical signals released by animals to communicate with other members of their species. Humans and many insect species alike release pheromones that function in attracting mates. Releasing the pheremones of insect pests can confuse males seeking mates and ultimately hinder them from reproducing (figure $14.4.g$). This "male confusion" has been successful against the pink bollworm that infests cotton and reduced the need for conventional chemical insecticides by 90%. Pheromones have also been successful against pests that attack tomatoes, grapes, and peaches. If targeted chemicals are not effective, IPM may employ conventional pesticides, ideally only applying them to the spots that they are needed and at the lowest effective concentration. Broadcast spraying of non-specific pesticides is a last resort.

Figure $14.4.g$: This pheromone trap is used to control the Asiatic rice borer. The caterpillars of this moth species infest rice stems. Image by Mehdi (CC-BY-SA).

Sustainable Practices to Maintain Soil Fertility

A variety of sustainable practices can maintain soil quality. Many of these strategies have additional benefits such as regulating pests, limiting climate change, and preventing water pollution. These methods enrich the soil with nutrients, ensure proper water holding capacity (ability of the soil to retain water), and limit soil-degrading processes such as erosion and compaction.

Crop Rotation

As previously mentioned, **crop rotations** are planned sequences of different crops over time on the same field (figure $14.4.h$). 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. 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.

Figure $14.4.h$: Crop rotation can be used at a large agricultural scale (left) or in a smaller garden (right). In each situation, which crop species are planted in each location changes year to year. Left image by USDA (public domain) and right image by Sten Porse (CC-BY-SA).

Intercropping

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 $14.4.i$). 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 14.4.i: Intercropping of beans and maize (corn). Beans have root nodules that house nitrogen-fixing bacteria, enriching the soil. Image by AnnaJB (CC-BY-SA).

A common example of strip cropping (a type of intercropping; see above) involves alternating a row crop such as corn with a ground-covering crop such as alfalfa. The ground-covering crop helps reduce water runoff and traps soil eroded from the row crop. If this ground-covering crop is a member of the legume family such as alfalfa or soybeans and is associated with nitrogen-fixing bacteria, then alternating the strips from one planting to the next can also help maintain topsoil fertility.

Cover Crops

Cover crops are those that are planted in the off-season to avoid leaving the soil bare. They can prevent soil and wind erosion, improve soil's physical and biological properties, supply nutrients, suppress weeds, improve the availability of soil water, and break pest cycles along with various other benefits. Cover crops are often members of the legume family and help enrich the soil with usable nitrogen. A single species or mix of cover crop species may be planted (figure 14.4.j).

Figure 14.4.j: A roller (crimper) on a tractor being used to roll down a rye and hairy vetch cover crop in April in the United States. While hairy vetch can limit soil erosion and add nitrogen to the soil, it is also an invasive species that must be carefully managed. Image and caption (modified) from Mr. 1032 (CC-BY-SA).

Agroforestry

Agroforestry is the process of planting rows of trees interspersed with a cash crop (figure $14.4.k - l$). Besides helping to prevent wind and water erosion of the soil, the trees provide shade which helps promote soil moisture retention. Decaying tree litter also provides some nutrients for the interplanted crops. The trees themselves may provide a cash crop. For example, fruit or nut trees may be planted with a grain crop. You can learn more about agroforestry using this interactive site by the United States Department of Agriculture and Forest Service.

Figure $14.4.k$: Through agroforestry, high-value non-timber crops (food, medicinal plants, woody florals, and crafts) can be cultivated under the protection of a forest canopy that has been managed to provide a favorable crop environment. Image and caption (modified) from USDA/UFS (public domain).

Contour and Terrace Farming

Contour farming involves plowing and planting crop rows along the natural contours of gently sloping land (figure $14.4.l$). The lines of crop rows perpendicular to the slope help to slow water runoff, inhibit the formation of channels of water, and limit soil erosion (and the resultant loss of nutrients). **Terracing** is a common technique used to control water erosion on more steeply sloped hills and mountains (figure $14.4.l$). Broad, level terraces are constructed along the contours of the slopes, and these act as dams trapping water for crops, reducing runoff, and limiting erosion.

Figure $14.4.l$: Contour farming (left) and terracing (right). In contour farming, rows of crops wave perpendicular to the slopes of the land. This example (left) also employs agroforestry. Terrace farming involves making step-like structures (terraces) perpendicular to the incline of a slope to reduce erosion. Left image by Pixture2016 (CC-BY-SA). Right image by USDA (public domain).

Minimal Tillage and No-till Agriculture

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. Another aspect of soil tillage (mixing the soil) 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 climate change.

One of the easiest ways to prevent these problems is to minimize the amount of **tillage**, or turning over of the soil. In **minimal tillage** (conservation tillage) or **no-till agriculture**, the land is disturbed as little as possible by leaving crop residue in the fields (figure $14.4.m$). Special seed drills inject new seeds and fertilizer into the unplowed soil. 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. With proper planning, minimal tillage and no-till agriculture can simultaneously limit soil erosion and compaction, protect soil organisms, reduce costs (if performed correctly), and promote water infiltration. Furthermore, carbon can actually become sequestered into the soil with these methods, thus mitigating climate change. Minimal or no-till agriculture have proved a major success in Latin

America and are being used in South Asia and Africa. However, a drawback of this method is that the crop residue can serve as a good habitat for insect pests and plant diseases.

Figure $14.4.m$: No-till agriculture is an important tool to prevent loss of soil moisture. Image by USDA (public domain).

Windbreaks

Creating **windbreaks** by planting tall trees along the perimeter of farm fields can help control the effects of wind erosion of soil (figure $14.4.n$). Windbreaks reduce wind speed at ground level, an important factor in wind erosion. They also help trap snow in the winter months, leaving soil less exposed. As a side benefit, windbreaks also provide a habitat for birds and animals. One drawback is that windbreaks can be costly to farmers because they reduce the amount of available cropland.

Figure $14.4.n$: Windbreaks are rows of trees and shrubs that reduce wind speed. They improve crop yields, reduce soil erosion, improve water-efficiency, protect livestock, and conserve energy. Image and caption (modified) from USDA/UFS (public domain).

Organic Agriculture

Organic agriculture is often incorporated into sustainable agriculture (figure $14.4.o$). To be certified as organic, farms must avoid using synthetic pesticides, synthetic fertilizers, and genetically modified organisms (figure $14.4.p$). Organic meat, poultry,

eggs, and dairy products come from animals that are given no antibiotics or growth hormones. Pests may instead be controlled by natural enemies or naturally produced substances such as neem oil or diatomaceous earth. Some organic alternatives to synthetic pesticides have relatively low environmental impact (such as salt spray), but there are many naturally produced compounds that are still toxic to people or cause ecological harm when widely used. Interestingly, external application of Bt toxin is approved for organic farming, but use of genetically engineered Bt crops is not. The latter results in lower concentrations of Bt toxin in the environment because it is locally produced directly by the plants themselves. In summary, although many practices of organic agriculture benefit the environment and meet sustainability goals, some organic farms are not sustainable and some sustainable farms are not organic.

Figure $14.4.o$: United States Department of Agriculture (USDA) Conservationist Shemekia Mosley (right) works with Nuri Icgoren (left) who operates Urban Sprout Farms, a biodynamic, certified organic urban farm Lakewood Heights, Georgia. Image and caption (modified) by Preston Keres/USDA (public domain).

Figure $14.4.p$: The USDA certified organic label. Modified from image by nikoretro (CC-BY-SA).

Consumer Choices that Support Sustainable Agriculture

Even if you're not a farmer or lawmaker, you have the power to promote sustainable agriculture as a consumer. As discussed in Food Chains and Food Webs, it generally requires more land and more energy to produce meat compared to plant-based foods due to the inefficient transfer of energy from one trophic level to the next. For this reason, plant-based diets tend to be more sustainable, but this depends on the types of foods consumed and how they were produced.

Local food is not only fresher, but it requires fewer food miles (figure $14.4.q$). In some ways, **organic food** causes less environmental degradation, but note that organic does not necessarily mean sustainable (see above). Because it limits machinery, synthetic pesticides, and synthetic fertilizers, it has a smaller **carbon footprint** (meaning it minimizes contribution to climate

change). The Clean 15 is a list of produce that is low in pesticide residues. If you can't afford all organic foods, these are the best items to purchase non-organic. Examples include avocados, sweet corn, and pineapple. The Dirty Dozen lists produce that has the most pesticide residues. If you can only afford a few organic items, these are best to purchase organic. Examples include strawberries, spinach, and nectarines. Finally, some foods, such as beef, have higher **carbon footprint** and **water footprint** than others.

Figure $14.4.q$: Farmers' markets are one option for purchasing locally grown foods. Image by NatalieMaynor (CC-BY).

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 (figure $14.4.r$). 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.

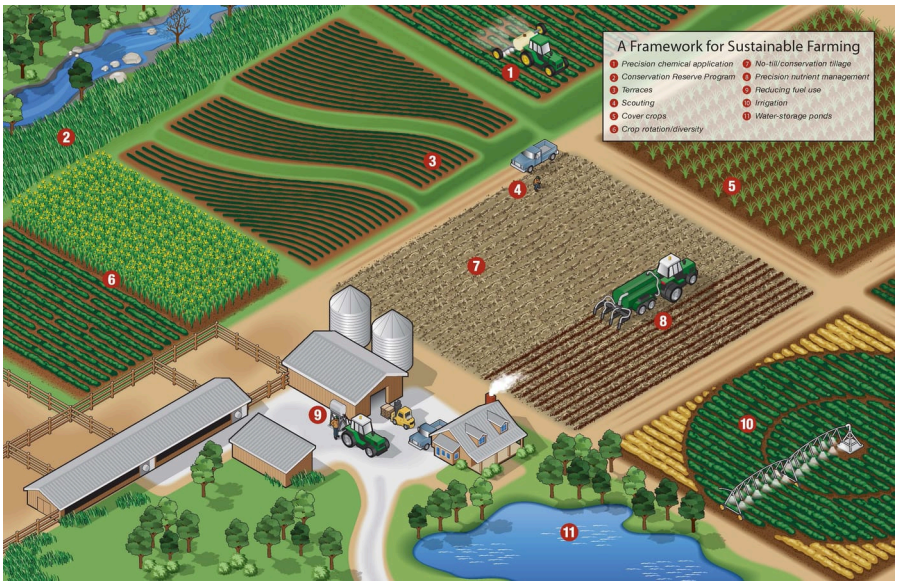

Figure $14.4.r$: Sustainable agriculture combines many approaches. (1) If chemical are used, they are applied only where needed. (2) Through the Conservation Reserve Program, the most ecologically important patches are left intact. (3) Terraces on slopes reduce soil erosion. (4) Crops are scouted for pests as part of monitoring, a component of integrated pest management. (5) Cover crops prevent erosion and enrich the soil during off-seasons. (6) Different types of crops are included are planted in close proximity (intercropping) or in different years (crop rotation). (7) Land is either not tilled at all or tilled minimally (conservation tillage). (8) Through precision nutrient management, soil is sampled at different locations, and fertilizer is only applied where needed. (9) Heavy equipment is used only as needed and in such a way that conserves fuel. (10) Irrigation is precisely timed to conserve water. (11) Water storage ponds help recharge groundwater. Image by the United Soybean Board (CC-BY).

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- Sustainability Definitions. USDA. Accessed 01-05-2021. (public domain)
- Biological Control from *Biology* by John W. Kimball (licensed under CC-BY)
- Integrated Pest Management (IPM) Principles. EPA. Accessed 01-05-2021 (public domain)
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14.5: Data Dive- Landslides and Ag Terraces

Overview

The beauty of terraced agriculture almost makes the observer forget that it is still a form of habitat destruction and landscape modification. A 2019 study investigated the risk to terraced landscapes with varying states of upkeep after severe rainfall events, which increase chances of serious damage due to landslide events. The authors compared three classes of upkeep:

- Succession on terrace: Which includes all terraced areas in which cultivation activities ceased, and is currently substituted by both wood and shrub cover.
- Cultivated terrace: Which includes all areas which are still under any kind of cultivation, from olive groves, to vineyards, to other crops
- Vegetated natural slopes: Which refer to those areas covered by spontaneous vegetation which have never been terraced.

Landslide mapping was used to estimate the size of damage after a landslide event took place. Below is a graph for some of the published results:

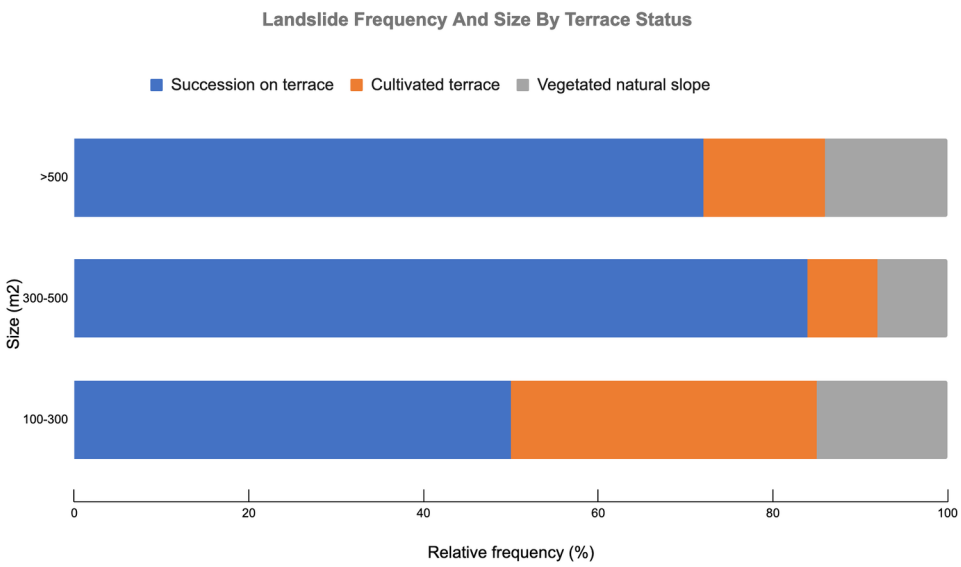

Figure $14.5.a$: Percent breakdown of landslide frequency and size by terrace status. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Agnoletti M, Errico A, Santoro A, Dani A, Preti F 2019.

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph?
3. Do the authors use any control category/variable to help clarify the patterns observed? If so, what?
4. Which status has the most consistent increased landslide frequency?
5. What landslide frequency patterns can you observe across the three size?
6. How can the results of this graph to inform future projects/restoration efforts when a terrace is abandoned?

Raw Data For Above Graph(s)

Table $14.5.a$**:** Raw data for percent breakdown of landslide frequency and size by terrace status. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Agnoletti M, Errico A, Santoro A, Dani A, Preti F 2019.

Terrace Status	100-300	300-500	Over 500
Succession On Terrace	50	84	72
Cultivated Terrace	35	8	14
Vegetated Natural Slope	15	8	14

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14.6: Review

Summary

After completing this chapter you should be able to...

- Describe the global state of food security.
- Compare industrial agriculture, sustainable agriculture, and organic agriculture.
- Define pests and pesticides.
- Detail the advantages and disadvantages of industrial agriculture.
- Compare selective breeding with genetic engineering.
- Explain how plants are genetically modified.
- Detail the advantages and disadvantages of using genetically modified crops.
- Explain the steps of integrated pest management and provide examples of cultural, mechanical, biological, and chemical control.
- Describe each sustainable practice that maintains soil quality and explain the additional benefits of these practices.

Progress continues in the fight against hunger, yet an unacceptably large number of people still lack the food they need for an active and healthy life. Food security is dependent on availability, access, and utilization.

Industrial agriculture is the prevailing agricultural system that relies on heavy machinery, synthetic pesticides, and synthetic herbicides. It has led to tremendous gains in productivity and efficiency worldwide. On the other hand, industrial agriculture has put small farms at a disadvantage and caused several ecological issues. It has exacerbated climate change, caused water pollution, degraded soil quality, harmed beneficial native organisms, and led to the evolution of pesticide resistance.

Both selective breeding and genetic engineering are processes of agricultural biotechnology. **Selective breeding** occurs when humans assist individual organisms with favorable traits in reproduction generation after generation. **Genetic engineering** refers to lab methods that directly alter an organism's DNA. Advocates say that application of genetic engineering in agriculture has resulted in benefits to farmers, producers, and consumers. While genetically modified organisms (GMOs) have potential to address malnutrition, reduce pesticide application, and combat crop disease, the companies who patent them now have greater control over agriculture. Furthermore, escaped transgenes can create herbicide-resistant superweeds. While members of the public have raised concerns about health impacts of GMOs, the National Academies of Sciences, Engineering, and Medicine's assessment of over 900 studies found that GMOs do not threaten human health.

Sustainable agriculture is an alternative to industrial agriculture that focuses on preserving natural resources and protecting the environment. It can thus be continued indefinitely. Sustainable agriculture employs **integrated pest management** (IPM), which relies on a variety of approaches to keep populations of true pests below economically harmful levels. Approaches with the lowest environmental impact are prioritized under IPM. A variety of sustainable practices such as crop rotation, intercropping, terrace farming, and minimal tillage can maintain soil fertility. Many of these methods additionally help regulate pest populations, preserve water quality, and combat climate change. **Organic agriculture** avoids using synthetic pesticides, synthetic fertilizers, GMOs, hormones, and antibiotics. Organic and sustainable farming practices often overlap. Consumers can promote sustainable agriculture by purchasing local, organic foods and choosing foods with low carbon and water footprints.

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15: ENVIRONMENTAL HEALTH

Chapter Hook

In 1854 England, a cholera epidemic started wiping out people within a day of symptoms starting. Only one physician, Dr John Snow, thought that it connected with contaminated water sources. Over the course of a month, Dr Snow was able to provide evidence that one particular well was connected with almost all of the deaths. Later, it was discovered that the contaminant in the water was a bacterium, named for the disease it caused, *Vibrio cholerae*. Unfortunately, cholera is not a disease of the past. The World Health Organization calculates an average of 1.3-4 million cases where an estimated 21-143,000 of these cases result in death. In some places, there is enough preventative testing to stop the spread of the disease before people get sick. However, in others, the contamination is unfortunately addressed only after an epidemic occurs.

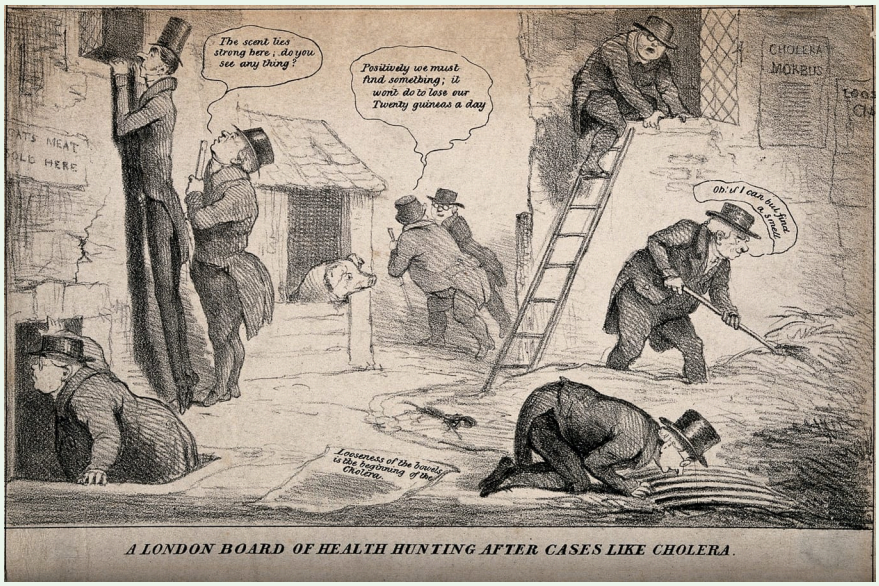

Figure 15.a: Cholera cartoon from 1854. Image by Wikimedia Commons (CC-BY-2.0)

15.1: Types of Environmental Hazards

15.2: Epidemiology

15.3: Infectious Diseases

15.4: Environmental Toxicology

15.5: Environmental Hazard Reduction

15.6: Data Dive- Cholera Cases Worldwide

15.7: Review

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15.1: Types of Environmental Hazards

Environmental health is a field that focuses on how the natural and human-built surroundings as well as behaviors affect human well-being. The field is concerned with preventing disease, death, and disability by reducing exposure to environmental hazards and promoting behavioral change. **Environmental hazards** are threats to human health and well-being (table $15.1.a$).

Table $15.1.a$: Typical Environmental Health Issues: Determinants and Health Consequences.

Underlying Determinants	Possible Adverse Health and Safety Consequences
Inadequate water (quantity and quality), sanitation and solid waste disposal, improper hygein (handwashing)	Diarrhea and vector-related diseases (for example, malaria, schistosomiasis, and dengue)
Improper water resource managment, uncluding poor drainage	Vector-related diseases
Crowded housing and poor ventialtion of smoke	Acute and chronic respiratory disease, including lung cancer from coal and tobacco 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 May also spread other infectious diseases (for example, HIV/AIDS, Ebola)
Exposure to naturally ocurring toxic substances	Poising from substances such as arsenic, manganese, and fluorides
Natural resources degradation (for example, landslides, poor drainage, erosion)	Injury and death from landslides and flooding
Climate change, partly from combustion of fossil fuel and release of greenhouse gases in transportation, industry, and poor energy conservation in housing, fuel, commerce, and industry	Injury/death from extreeme heat/cold, sotres, floods, and fires Indirect effects spread of vectorbrone diseases, aggravation of respriatory diseases, population dislocation, water pollution from sea level rise, etc.
Ozone depletion from industrial and commercial actvitiy	Skin cancer, cataracts Indirect effect: compromised food production

Table based on Lvovsky/World Bank (CC-BY)

Traditional versus Modern Environmental Hazards

Environmental hazards can be classified as traditional or modern. **Traditional hazards** are related to poverty and mostly affect low-income people and those in developing countries. **Modern hazards**, caused by technological development, prevail in industrialized countries where exposure to traditional hazards is low.

The impact of traditional hazards exceeds that of modern hazards by 10 times in Africa, five times in Asian countries (except for China), and 2.5 times in Latin America and the Middle East (figure $15.1.a$). 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, 90,000

children under five died diarrhea in 2017. Globally, 409,000 people died of malaria in 2019 with 94% of these deaths occurring in African countries. In 2016, approximately one third of the world's households used unprocessed solid fuels, particularly biomass (crop residues, wood, and dung) for cooking and heating in inefficient stoves without proper ventilation. This exposes people—mainly low-income women and children—to high levels of indoor air pollution, the cause of about 1.6 million deaths in each year (figure $15.1.b$).

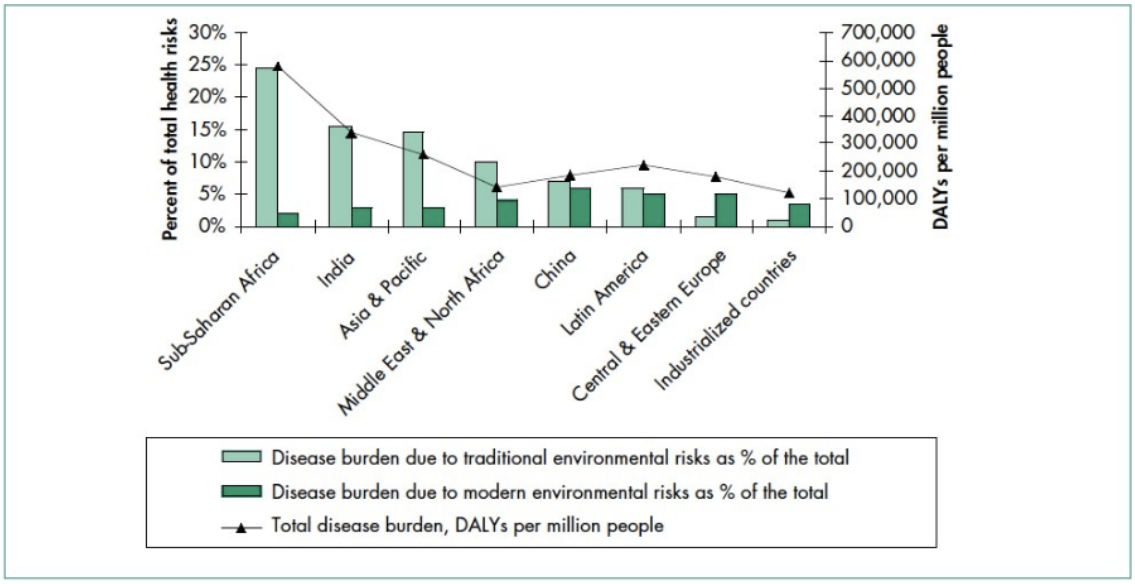

Figure $15.1.a$: The percent of total health risks due to traditional (light green bars on the left) versus modern (dark green bars on the right) health risks and total disease burden (line and triangles) in disability-adjusted life years (DALY) per million people in eight regions. The disability-adjusted life years measures the burden of disability associated with a disease or disorder and represent represent the total number of years lost to illness, disability, or premature death within a given population. Traditional environmental health hazards prevail in developing countries, but modern risks are also significant. Traditional hazards are greatest in Sub-Saharan Africa (25%), and modern hazards are greatest in China (5%), Latin America (4%), and Central and Eastern Europe (4%). For most regions, traditional hazards were a greater threat than modern hazards with the exceptions of Central and Eastern Europe and industrialized countries. Image from World Bank (CC-BY).

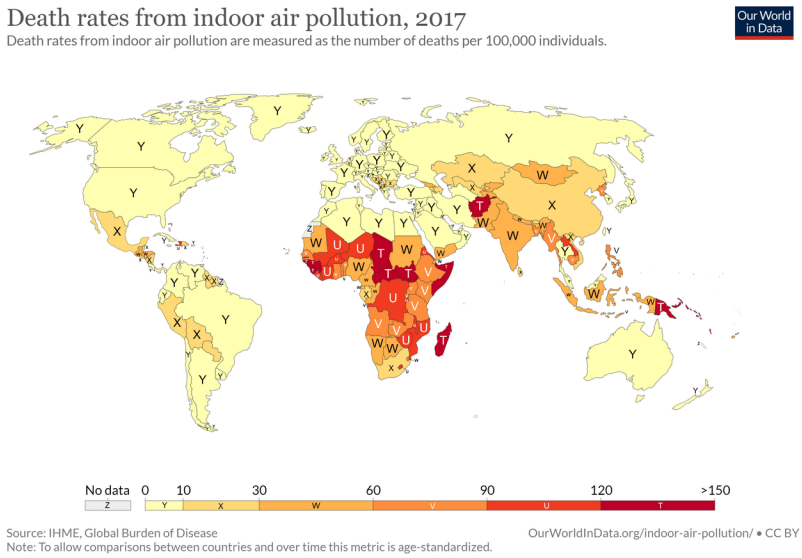

Figure $15.1.b$: Death rates from indoor air pollution in each country in 2017. Guinea, Sierra Leone, Chad, Central African Republic, South Sudan, Somalia, Madagascar, Afghanistan, and Papua New Guinea had the highest death rates (more than 120 deaths per 100,000 individuals, T). Moderately high death rates (90-120 deaths per 100,000 individuals, U) were mostly in African and Southeast Asian countries. Moderate death rates (30-90 deaths per 100,000 individuals, W and V) were mostly in African and Asian countries. Moderately low death rates (10-30 deaths per 100,000 individuals, X) were in Central and South America and northern Asia. The lowest death rates were (0-10 deaths per 100,000 individuals, Y) were in mostly in North American, South American, European, and North African countries and Australia. Image modified from Hannah Ritchie (2013). Indoor Air Pollution. Published online at OurWorldInData.org. (CC-BY).

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 (figure $15.1.a$). Urban air pollution, for example, is highest in parts of China, India, and some cities in Asia and Latin America. Low-income people increasingly experience a "**double burden**" of traditional and modern environmental health risks. In rich countries, they experience twice the burden of illness and death from all causes and 10 times greater disease burden from environmental risks.

Biological, Chemical, and Physical Environmental Hazards

Environmental hazards can also be classified into three interrelated categories (biological, chemical, and physical) based on the properties of their causes. These categories are not mutually exclusive with traditional versus modern hazards. For example, indoor air pollution is both a traditional and chemical hazard. Different hazards can interact and exacerbate one another. For example, a flood is primarily a physical hazard, but it can lead to the spread of waterborne disease (a biological hazard). Similarly, air pollution (a chemical hazard) can damage respiratory tissue, making the body more vulnerable to a respiratory infection (a biological hazard). Infectious diseases (biological hazards) can also weaken the immune system, making an individual more vulnerable to chemical hazards.

Biological Hazards

For most of human history, biological hazards were the most significant factor in health. **Biological hazards** are infectious (communicable) diseases caused by **pathogens** (disease-causing organisms or infectious particles) such as bacteria, fungi, parasitic worms, protozoa, viruses, and prions. **Bacteria** are single-celled organisms with small, simple cells. Examples of bacterial diseases include tuberculosis, cholera, bacterial pneumonia, and dysentery. **Fungi** may have one or multiple cells and have a more complex cell type than bacteria. Fungal diseases include minor infections like candidiasis (yeast infection) or athlete's foot, but they can also causes severe respiratory infections (histoplasmosis, coccidioidomycosis, etc.) particularly in individuals with compromised immune systems. **Parasitic worms** are animals from several phyla (groups) that siphon nutrients from their hosts. Examples include tapeworms, commonly acquired through consuming undercooked meat, and blood flukes (*Schistosoma*). Like fungi, **protozoa** have larger, more complex cells than bacteria, but they are single celled and lack the rigid

cell wall that surrounds fungal cells. Malaria (figure $15.1.c$), African trypanosomiasis (sleeping sickness), and giardiasis are caused by protozoa. **Viruses** are infectious particles with genetic information surrounded by a protein coat, but they are not technically considered organisms in part because they do not consist fo cells. COVID-19, influenza, measles, the common cold, ebola viral disease (Ebola hemorrhagic fever), and human immunodeficiency virus (HIV)/acquired immune deficiency syndrome (AIDS) are all caused by viruses. **Prions** (proteinaceous infectious particles) are even simpler than viruses because they lack genetic material and only contain protein.

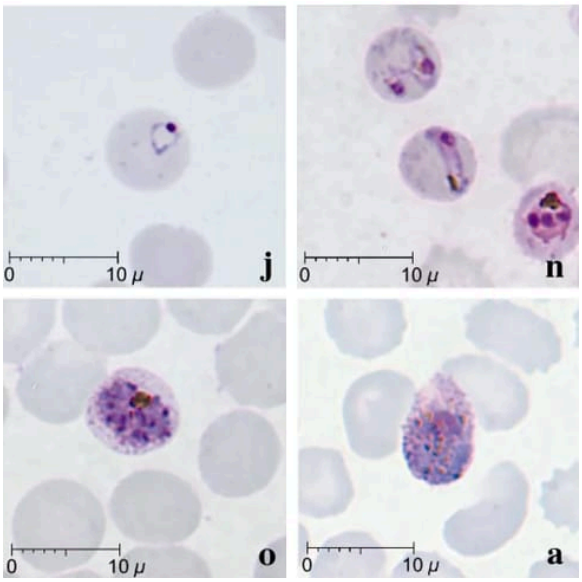

Figure $15.1.c$: Red blood cells infected with the protozoan *Plasmodium*, which causes malaria, under the microscope. Image by Kim-Sung Lee, Janet Cox-Singh, Balbir Singh (CC-BY).

While the proportion of deaths caused by in infectious diseases has overall decreased (with a higher proportion of deaths caused by noncommunicable diseases such as cancer and cardiovascular disease), infectious diseases still caused about one in five deaths in 2017. These deaths occurred at the highest rates in developing countries and many were in children. Malnutrition, unclean water, poor sanitary conditions and lack of proper medical care all play roles in transmission and high death rates from infectious diseases Compounding the problems of infectious diseases are factors such as antibiotic-resistant pathogens, pesticide-resistant disease vectors, and overpopulation.

Chemical Hazards

Chemical hazards are toxic substances, which cause damage to living organisms. Air pollutants (such as secondhand smoke or carbon monoxide), heavy metals, and pesticides are a few examples. We can be exposed to these contaminants from a variety of residential, commercial, and industrial sources. Sometimes harmful environmental contaminants occur biologically, such as those from mold or a toxic algae bloom. Toxins can be classified based on their origin, purpose, chemical structure and properties, or effects. Table $15.1.b$ describes a few categories of toxins based on their effects and provides examples. A few of these examples are discussed more specifically below.

Table $15.1.b$***:*** *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.

Contaminant	Definition
Mutagen	A material that induces genetic changes (mutations) in the DNA. Examples include radioactive substances (such as radon and nuclear fuel and waste) and nitrous acid. Some forms of radiation (see Physical Hazards) are also mutagens.
Neurotoxin	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, per- and polyfluoroalkyl substances (PFAS), pthalates, and plasticizers such as bisphenol A (BPA).

Formaldehyde

Formaldehyde is a colorless, flammable gas or liquid that has a pungent, suffocating odor. It is a **volatile organic compound**, which is a compound containing carbon and hydrogen 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. Formaldehyde is released into the air by industries using or manufacturing formaldehyde, wood products (such as particle-board, plywood, and furniture), automobile exhaust, cigarette smoke, paints and varnishes, and carpets and permanent press fabrics. Nail polish and commercially applied floor finish emit formaldehyde (figure $15.1.d$).

Figure $15.1.d$: Nail products are known to contain toxic chemicals, such as dibutyl phthalate (DBP), toluene, and formaldehyde.

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

Heavy Metals

Heavy metals are chemical elements of high density that form a special type of bond (called metallic bonds, in which electrons are shared but in a less constricted way than in covalent bonds). Arsenic, mercury, lead, and cadmium are examples of heavy metals.

Arsenic (As) 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 railings 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.

Arsenic poisoning causes a variety of symptoms and serious health conditions (figure $15.1.e$). 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.

Figure $15.1.e$: Patchy areas of dark skin pigmentation (arsenical hyperkaratosis) on the palms of the hands is a symptom of arsenic poisoning. Image and caption (modified) from Agency for Toxic Substances and Disease Registry/CDC (public domain).

Mercury (Hg) 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 (Biomagnification). 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. The United States Environmental Protection Agency thus 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 such as salmon, shrimp, pollock, and catfish (figure $15.1.f$). 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 (figure $15.1.g$).

Figure $15.1.f$: Fish classified based on mercury levels. The best choices (black sea bass, catfish, herring, trout, and many others) have the lowest mercury levels, and two or three servings of these choices can be safely consumed each week. The good choices (carp, halibut, yellowfin tuna, etc.) have moderate levels, and it is safe to eat one serving per week. The choices to avoid, such as shark and swordfish, have the highest mercury levels and should be avoided. A table listing all fish in each category is available here. Image by EPA and FDA (public domain).

Figure $15.1.g$: Button-cell batteries found in small devices like watches and hearing aids contain mercury and must be discarded at the proper hazardous waste facility. Image by Lead holder (CC-BY-SA).

Lead (Pb) is a metal that occurs naturally in the rocks and soil of the Earth's crust. It is also released from mining, manufacturing, and the combustion (burning) fossil fuels such as coal, oil, gasoline, and natural gas. Lead has no distinctive taste or smell. 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.

The video below explains how Flint, Michigan's water supply was polluted with lead in 2014 and the problematic government response that followed. This video was made in 2016. As of 2020, Flint has a clean water source, and the city of Flint is in the process of compensating affected residents for the damages. (Click here to read a 2020 update.)

YouTube Video

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

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Asbestos

Asbestos is a mineral fiber that occurs in rock and soil. Because of its fiber strength and heat resistance asbestos has been used in a variety of building construction materials for insulation and as a fire retardant. Asbestos has also been used in a wide range of manufactured goods, mostly in building materials (roofing shingles, ceiling and floor tiles, paper products, and asbestos cement products), friction products (automobile clutch, brake, and transmission parts), heat-resistant fabrics, packaging, gaskets, and coatings. Exposure to asbestos is associated with cancers (lung cancer and mesothelioma) and another lung disease called asbestosis. In the United States, certain uses of asbestos, including in corrugated paper, flooring, and building insulation, are banned under the Toxic Substances Control Act and Clean Air Act (figure $15.1.h$). In contrast, asbestos is fully banned in 67 countries as of 2019.

Figure $15.1.h$: An asbestos pipe wrap. While this use of asbestos is banned in the United States, other uses are still permitted. Image by EPA (public domain).

Per- and polyfluoroalkyl substances (PFAS)

Per- and polyfluoroalkyl substances (PFAS) are a group of manufactured organic chemicals used in a variety of industries (figure $15.1.i$). They can be found in food packaging, stain- and water-repellent fabrics, nonstick products (such as Teflon), polishes, waxes, paints, cleaning products, and fire-fighting foams.

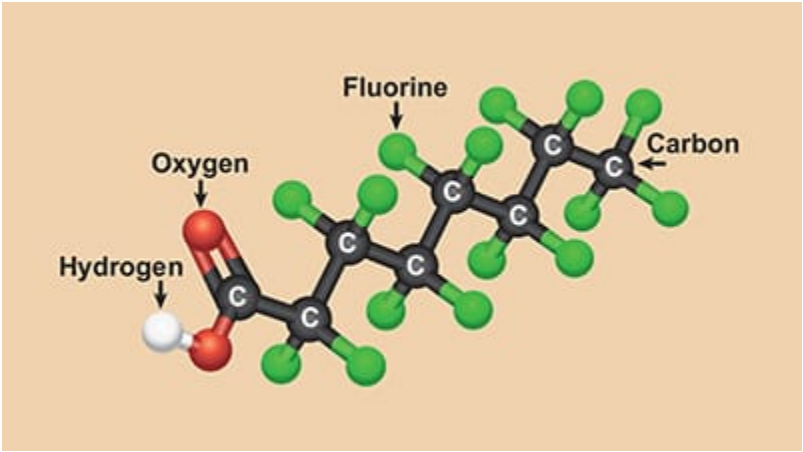

Figure $15.1.i$: The chemical structure of perfluorooctanoic acid (PFOA), a PFAS. This molecule has eight carbon atoms (black) connected in a chain. Most of them are bound to fluorine atoms (green). The carbon at the end of the chain forms two covalent bonds with an oxygen and is single bounded to another oxygen atom, which is also attached to a hydrogen. Image by National Institute of Environmental Health Sciences (public domain).

Studies indicate that some PFAS can cause reproductive and developmental, liver and kidney, and immunological effects in laboratory animals. More limited findings associate some PFAS with low infant birth weights, effects on the immune system, cancer, and thyroid hormone disruption in humans.

Eight major chemical manufacturers in the U.S. phased out the use certain PFAS (called perfluorooctanoic acid, PFOA, and perfluorooctane sulfonate, PFOS) and related chemicals in their products and as emissions from their facilities. However, these PFAS can still be imported and other PFAS are still manufactured in the U.S.

Polychlorinated Biphenyls (PCBs)

Polychlorinated biphenyls (PCBs) are a group of manufactured organic chemicals. They belong to a broad family of chemicals known as chlorinated hydrocarbons, which consisting of carbon, hydrogen and chlorine atoms (figure $15.1.j$). The number of chlorine atoms and their location in a PCB molecule determine many of its physical and chemical properties. PCBs have no known taste or smell, and range in consistency from an oil to a waxy solid.

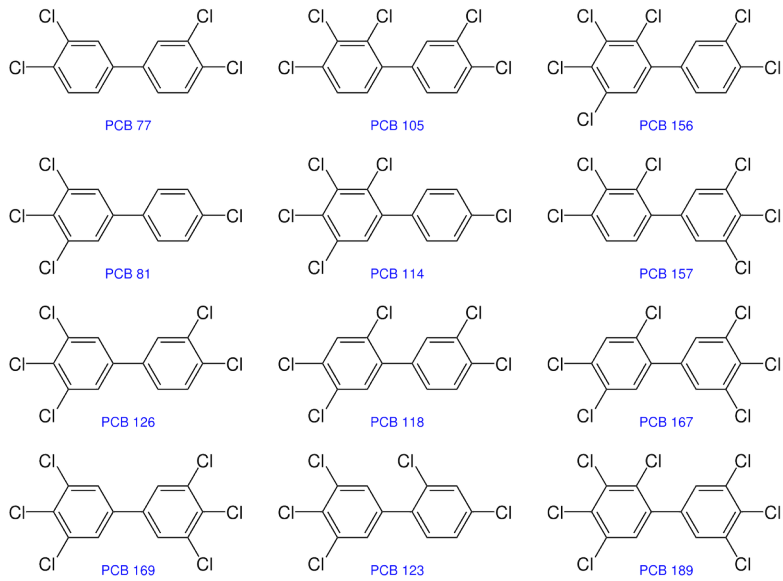

Figure $15.1.j$: A variety of polychlorinated biphenyls (PCBs). They each have two rings of six carbon atoms each attached together. Additionally, each has multiple chlorine atoms attached to the rings, but the exact number and placement of chlorine atoms varies. Image by Leyo/M. Van den Berg et al. (public domain).

Polychlorinated biphenyls have been shown to cause cancer, cause birth defects, and affect the immune, reproductive, nervous, and endocrine systems in animals. Studies in humans support evidence for potential carcinogenic and non-carcinogenic effects of PCBs. The different health effects of PCBs may be interrelated. Alterations in one system may have significant implications for the other systems of the body.

The manufacture of PCBs in the U.S. began in 1929 until it was banned in 1979 under the Toxic Substances Control Act. Due to their non-flammability, chemical stability, high boiling point and electrical insulating properties, PCBs were used in hundreds of industrial and commercial applications including in electrical equipment, coolants paints, plastics, rubber products, pigments, and dyes.

Bisphenol A (BPA)

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 such as water and infant bottles, impact-resistant safety equipment, and medical devices (figure $15.1.k$). 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. It has also be found in breast milk.

Figure 15.1.k: A water bottle is labeled as BPA free. Image by Hteink.min (CC-BY-SA).

Some animal studies suggest that infants and children may be the most vulnerable to the effects of BPA. It disrupts signaling by estrogen, a naturally produced hormone, and the U.S. National Toxicology Program (NTP) documented concerns about its effects on the behavior, brain, and prostate in young children and developing fetuses.

The following personal choices can reduce exposure to BPA:

- Avoid microwaving polycarbonate plastic food containers. Polycarbonate is strong and durable, but over time it may break down from over use at high temperatures.
- Note recycle codes on the bottom of plastic containers. 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.

While BPA is not banned in the U.S., the Food and Drug Adminsitration banned its use in baby bottles and sippy cups in 2012 and its use in the coating of infant formula containers in 2013. However, similar compounds such as bisphenol S (BPS) are now used as replacements.

Phthalates

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 (figure 15.1.l). 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.

Figure $15.1.l$: Phthalates are often used in shampoos and other personal care products, but some brands produce phthalate-free products. Image by inf per Open Food Facts (CC-BY-SA).

Phthalates are suspected to be endocrine disruptors. Some types of phthalates have affected the reproductive system of laboratory animals. In 2017, The U.S. Consumer Product Safety Commission (CPSC) has banned several pthalates from being used at concentrations greater than 0.1% in toys and products designed to be used by children three years old or younger.

Radon

Radon is a radioactive gas that is naturally-occurring, colorless, and odorless (figure $15.1.m$). 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. To reduce the risk of radon exposure, the Department of Urban and Housing Development recommends testing your home for radon, avoiding smoking to reduce the risk of lung cancer, and ensuring proper ventilation in your home.

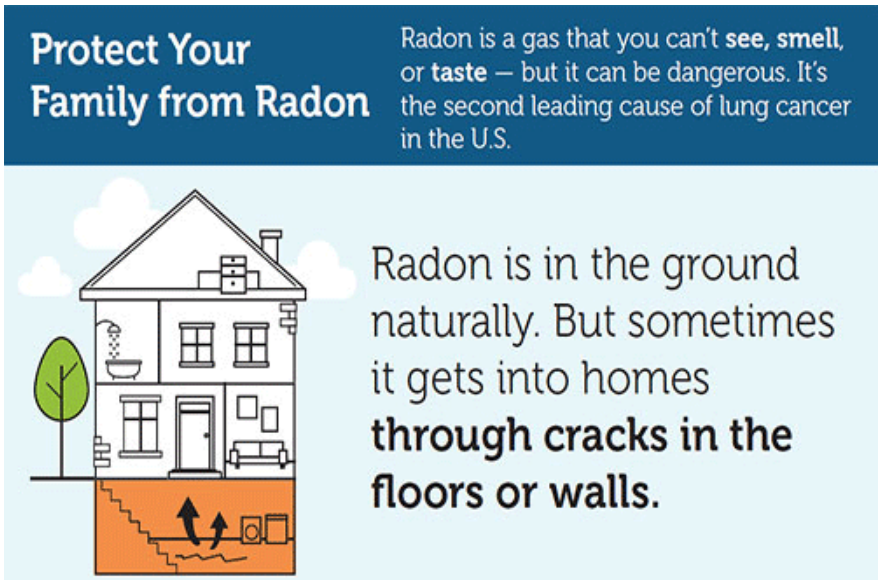

Figure $15.1.m$: This information graphic from the Centers for Disease Control explains how people can be exposed to radon from underground and its health risks. It reads "Protect your family from radon. Radon is a gas that you can't see, smell, or taste— but it can be dangerous. It's the second leading cause of lung cancer in the U.S. Radon is in the ground naturally. But sometimes it gets into homes through cracks in the floors or walls." Image by CDC (public domain).

Dichlorodiphenyltrichloroethane (DDT)

Dichlorodiphenyltrichloroethane (DDT) was the first of a long line of chlorinated hydrocarbon insecticides (figure $15.1.n$). These compounds are chains of carbon and hydrogen with chlorine atoms replacing some of the hydrogen atoms. Introduced during World War II, DDT, along with penicillin and the sulfa drugs, was responsible for the fact that this was the first war in history where trauma killed more people - combatants and noncombatants alike - than infectious disease.

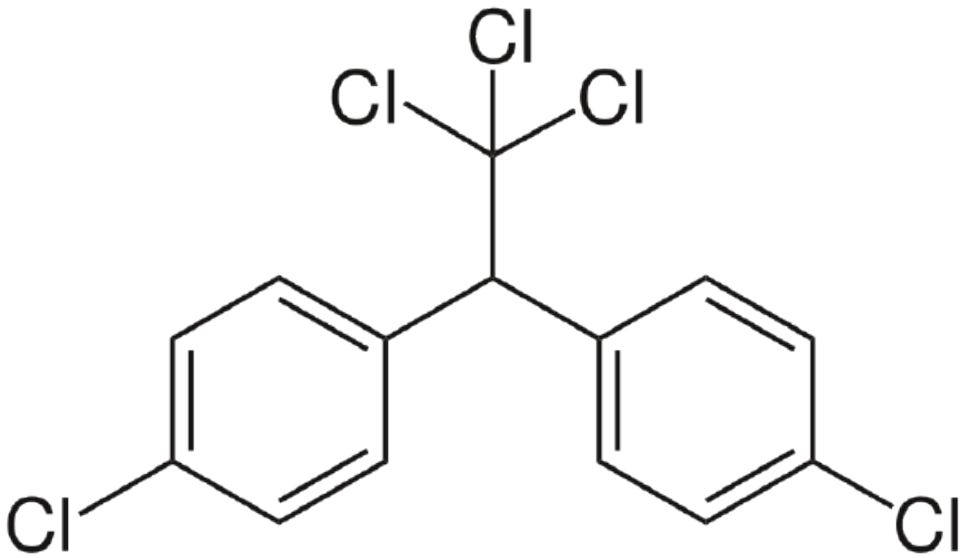

Figure $15.1.n$: DDT was a commonly-used pesticide. The bag of DDT on the right says, "Insect spray containing 50% DDT. Destroys many common insects. Use on potatoes, peas, corn, fruits, and ornamentals." Left image by Leyo (public domain), and right image by Xanthis (public domain).

Dichlorodiphenyltrichloroethane is effective against many crop pests as well as vectors of human diseases such as the mosquitoes that spread malaria and yellow fever and fleas, which transmit the plague. Prior to the introduction of DDT, the number of cases of malaria in Ceylon (now Sri Lanka) was more than a million a year. By 1963 the disease had been practically eliminated from the island. However, growing concern about the hazards of DDT led to its abandonment there in the mid-1960s, and soon thereafter malaria became common once again. Because it remains in the environment and is resistant to breakdown, DDT was especially effective against malarial mosquitoes. One or two sprays a year on the walls of homes kept them free of mosquitoes. It was also inexpensive, further adding to its appeal, but DDT has several serious drawbacks.

Because DDT builds up in fatty tissues (bioaccumulation) and becomes more concentrated at the highest levels of the food chain (biomagnification), it is especially harmful to apex predators, such as Bald Eagles (figure $15.1.o$). Classical studies documenting these effects were described in the 1960s bestseller *Silent Spring* by Rachel Carson. It was discovered that DDT caused the eggshells of birds to become fragile and break, making reproduction impossible. As a result, the Bald Eagle was listed as an endangered species under U.S. law. After DDT was banned in the United States in 1972, affected bird populations made noticeable recoveries, including the iconic Bald Eagle.

Figure $15.1.o$: DDT pesticide residue in fish and other prey poisoned Bald Eagles, causing egg shell thinning that resulted in widespread nesting failures. Image by Ron Holmes/USFWS (public domain).

Physical Hazards

Physical hazards are additional forces that can imperil humans. Physical hazards may arise naturally such as natural disasters (earthquakes, wildfires, landslides, etc.) or extreme weather (figure $15.1.p$). Others may arise from human structures or activities (traffic accident, building collapse, injury from mechanical equipment, strain on the body from repeated movements, etc.) Some physical hazards, such as explosions or radiation, can arise from natural or human sources.

Figure $15.1.p$: This section of E. Grace Street, Richmond, VA, collapsed during tropical storm Gaston. Gaston dropped twelve inches of rain in the area. Image by Liz Roll/FEMA Photo Library (public domain).

Radiation is energy given off by matter in the form of rays or high-speed particles, and some types of radiation present a physical hazard. Some familiar forms of radiation are infrared radiation (heat), visible light, ultraviolet (UV) light, radio waves, and microwaves. We are exposed to radiation every day from natural sources. For example, the sun exposes us to UV radiation. We

are also exposed to radiation from human-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. Some types of radioactive materials are more dangerous than others. Specifically, **ionizing radiation**, like X rays and gamma rays (one of the forms of radiation emitted from nuclear fuel and waste), have enough energy to break molecular bonds and displace (or remove) electrons from atoms.

Attribution

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  - Environmental Health
  - Environmental Toxicology
  - Pests and Pesticides
  - Energy Flow through Ecosystems
- Insecticides from *Biology* by John W. Kimball (licensed under CC-BY)
- Impact on Human Health from *AP Environmental Science* by University of California College Prep (licensed under CC-BY)
- Environmental Health at a glance. 2003. World Bank. Washington, DC. (licensed under CC-BY)
- Asbestos. 2018. Environment Protection Agency. Accessed 01-07-2021. (public domain)
- Per- and Polyfluoroalkyl Substances (PFAS). 2018. Environment Protection Agency. Accessed 01-07-2021. (public domain)
- Polychlorinated Biphenyls (PCBs). 2020. Environment Protection Agency. Accessed 01-08-2021. (public domain)
- What are DALYs? National Institute of Mental Health. Accessed 01-06-2021. (public domain)
- Radiation Basics. 2020. U.S. NRC. Accessed 01-07-2021 (public domain)
- Phthalates. 2017. National Biomonitoring Program. Centers for Disease Control. Accessed 01-08-2021. (public domain)

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15.2: Epidemiology

The field of **epidemiology** studies the geographical distribution and timing of infectious disease occurrences and how they are transmitted and maintained in nature, with the goal of recognizing and controlling outbreaks. The science of epidemiology includes **etiology** (the study of the causes of disease) and investigation of disease transmission (mechanisms by which a disease is spread). **Epidemiologists** are thus scientists who study the causes and patterns of human disease, which involves examining statistics to identify health threats and recommending strategies to reduce these threats.

The work of epidemiologist Alice Wang is highlighted in the video below. While many of the examples on this page focus on infectious disease (which result from biological hazards), epidemiologists can study noncommunicable diseases too (such as poisoning or obesity). The text at the end of the video says, "Are You CDC? For more information bout employment opportunities with CDC, please visit: jobs.cdc.gov".

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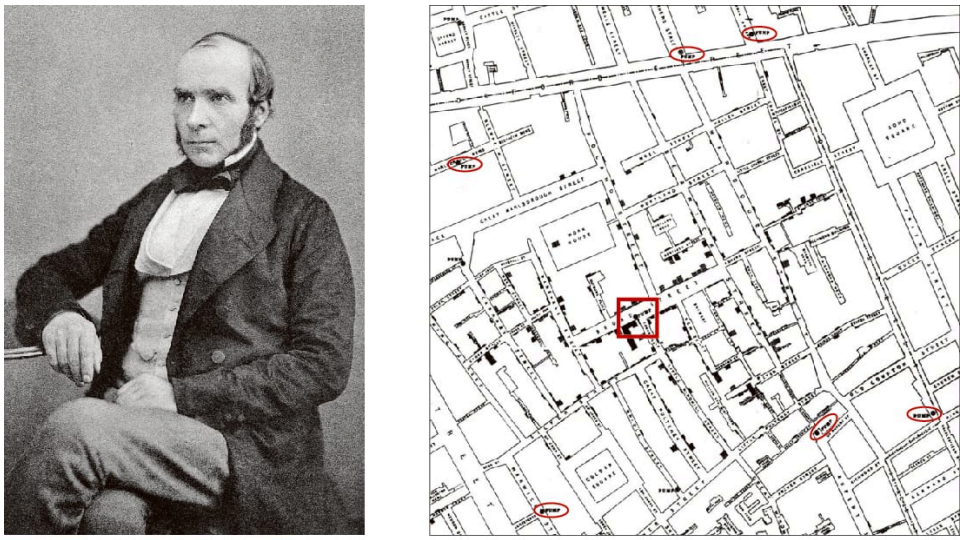
History of Epidemiology

The studies of 19th century physicians and researchers such as John Snow, Florence Nightingale, Ignaz Semmelweis, Joseph Lister, Robert Koch, Louis Pasteur, and others sowed the seeds of modern epidemiology.

John Snow (figure $15.2.a$) was a British physician known as the father of epidemiology for determining the source of the 1854 Broad Street cholera epidemic in London. Based on observations he had made during an earlier cholera outbreak (1848–1849), Snow proposed that cholera was spread through a fecal-oral route of transmission and that a microbe was the infectious agent. He investigated the 1854 cholera epidemic in two ways. First, suspecting that contaminated water was the source of the epidemic, Snow identified the source of water for those infected. He found a high frequency of cholera cases among individuals who obtained their water from the River Thames downstream from London. This water contained the refuse and sewage from London and settlements upstream. He also noted that brewery workers did not contract cholera and on investigation found the owners provided the workers with beer to drink and stated that they likely did not drink water. Second, he also painstakingly mapped the incidence of cholera and found a high frequency among those individuals using a particular water pump located on Broad Street. In response to Snow's advice, local officials removed the pump's handle, resulting in the containment of the Broad Street cholera epidemic. John Snow's own account of his work has additional links and information.

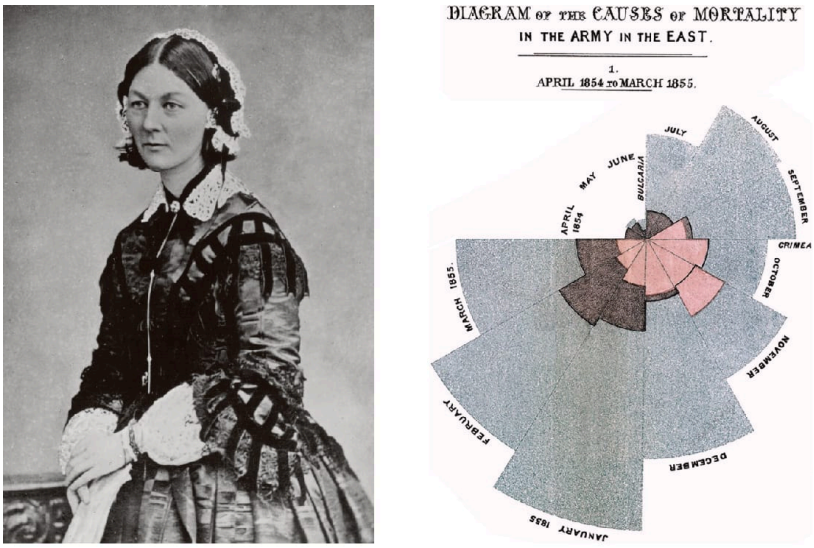


(a) (b)

Figure $15.2.a$: (a) John Snow (1813–1858), British physician and father of epidemiology. (b) Snow's detailed mapping of cholera incidence led to the discovery of the contaminated water pump on Broad street (red square) responsible for the 1854 cholera epidemic. (credit a: modification of work by "Rsabbatini"/Wikimedia Commons)

Snow's work represents an early epidemiological study and it resulted in the first known public health response to an epidemic. Snow's meticulous case-tracking methods are now common practice in studying disease outbreaks and in associating new diseases with their causes. His work further shed light on unsanitary sewage practices and the effects of waste dumping in the Thames. Additionally, his work supported the germ theory of disease, which argued disease could be transmitted through contaminated items, including water contaminated with fecal matter.

Florence Nightingale's work is another example of an early epidemiological study. In 1854, Nightingale was part of a contingent of nurses dispatched by the British military to care for wounded soldiers during the Crimean War. Nightingale kept meticulous records regarding the causes of illness and death during the war. Her recordkeeping was a fundamental task of what would later become the science of epidemiology. Her analysis of the data she collected was published in 1858. In this book, she presented monthly frequency data on causes of death in a wedge chart histogram (figure $15.2.b$). This graphical presentation of data, unusual at the time, powerfully illustrated that the vast majority of casualties during the war occurred not due to wounds sustained in action but to what Nightingale deemed preventable infectious diseases. Often these diseases occurred because of poor sanitation and lack of access to hospital facilities. Nightingale's findings led to many reforms in the British military's system of medical care. Learn more about Nightingale's wedge chart here.



(a) (b)

Figure $15.2.b$: (a) Florence Nightingale reported on the data she collected as a nurse in the Crimean War. (b) Nightingale's diagram shows the number of fatalities in soldiers by month of the conflict from various causes. The total number dead in a particular month is equal to the area of the wedge for that month. The colored sections of the wedge represent different causes of death: wounds (pink), preventable infectious diseases (gray), and all other causes (brown).

Joseph Lister provided early epidemiological evidence leading to good public health practices in clinics and hospitals. Most physicians did not wash their hands between patient visits or clean and sterilize their surgical tools. Lister, however, discovered the disinfecting properties of carbolic acid, also known as phenol. He introduced several disinfection protocols that dramatically lowered post-surgical infection rates. He demanded that surgeons who worked for him use a 5% carbolic acid solution to clean their surgical tools between patients, and even went so far as to spray the solution onto bandages and over the surgical site during operations (figure $15.2.c$). He also took precautions not to introduce sources of infection from his skin or clothing by removing his coat, rolling up his sleeves, and washing his hands in a dilute solution of carbolic acid before and during the surgery.

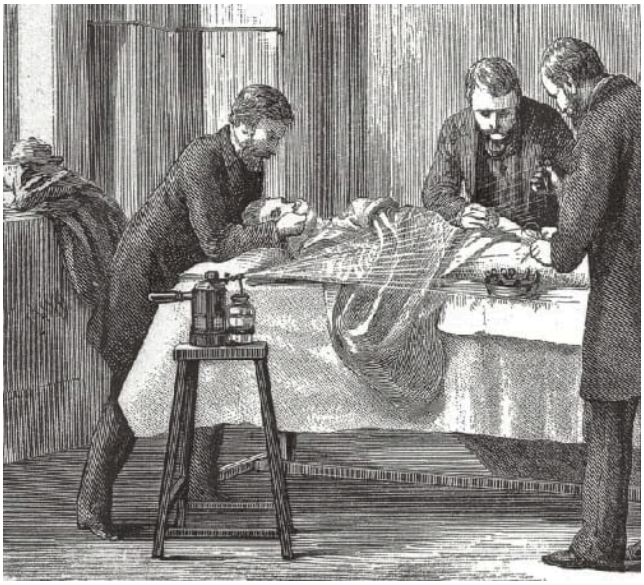


Figure $15.2.c$: Joseph Lister initiated the use of a carbolic acid (phenol) during surgeries. This illustration of a surgery shows a pressurized canister of carbolic acid being sprayed over the surgical site.

Analyzing Disease in a Population

Epidemiological analyses are always carried out with reference to a population, which is the group of individuals that are at risk for the disease or condition. The population can be defined geographically, but if only a portion of the individuals in that

area are susceptible, additional criteria may be required. Susceptible individuals may be defined by particular behaviors, such as intravenous drug use, owning particular pets, or membership in an institution, such as a college. Being able to define the population is important because most measures of interest in epidemiology are made with reference to the size of the population.

The state of being diseased is called **morbidity**. Morbidity in a population can be expressed in a few different ways. Morbidity, or **total morbidity,** is expressed in numbers of individuals without reference to the size of the population. The **morbidity rate** can be expressed as the number of diseased individuals out of a standard number of individuals in the population, such as 100,000, or as a percent of the population.

There are two aspects of morbidity that are relevant to an epidemiologist: a disease's prevalence and its incidence. **Prevalence** is the number, or proportion, of individuals with a particular illness in a given population at a point in time. For example, the Centers for Disease Control and Prevention (CDC) estimated that about 1.2 million people in the United States lived with an active human immunodeficiency virus (HIV) infection in 2018. Expressed as a proportion, or rate, this is a prevalence of 367 infected persons per 100,000 in the population. On the other hand, **incidence** is the number or proportion of new cases in a period of time. For the same year, the CDC estimates that there were 36,400 newly diagnosed cases of HIV infection, which is an incidence of 11.1 new cases per 100,000 in the population. The relationship between incidence and prevalence can be seen in figure $15.2.d$. For a chronic disease like HIV infection, prevalence will generally be higher than incidence because it represents the cumulative number of new cases over many years minus the number of cases that are no longer active (because the patient died or was cured).

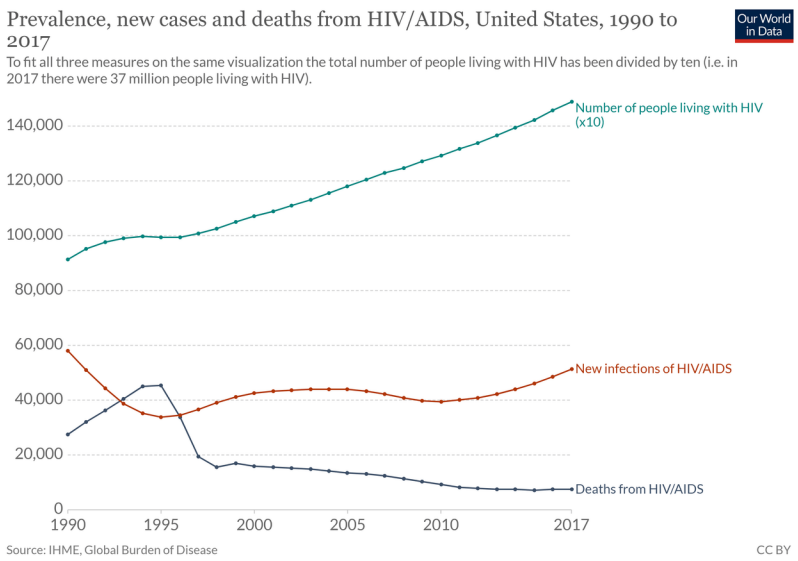


Figure $15.2.d$: The number of people living with HIV (prevalence), new infections of HIV/AIDS (incidence), and deaths from HIV/AIDs in the United States from 1990 to 2017. Prevalence and incidence can also be expressed as a rate or proportion for a given population. The number of people living with HIV has increased over time, but the number of new infections has fluctuated. Deaths reached a high around 1995 and have since declined. Image by Max Roser and Hannah Ritchie (2018) - "HIV / AIDS". Published online at OurWorldInData.org. (CC-BY).

In addition to morbidity rates, the incidence and prevalence of **mortality** (death) may also be reported. A mortality rate can be expressed as the percentage of the population that has died from a disease or as the number of deaths per 100,000 persons (or other suitable standard number).

Patterns of Incidence

Diseases that are seen only occasionally, and usually without geographic concentration, are called **sporadic diseases**. Examples of sporadic diseases include tetanus, rabies, and plague. In the United States, *Clostridium tetani*, the bacterium that causes tetanus, is ubiquitous in the soil environment, but incidences of infection occur only rarely and in scattered locations because most individuals are vaccinated, clean wounds appropriately, or are only rarely in a situation that would cause infection. Likewise in the United States there are a few scattered cases of plague each year, usually contracted from rodents in rural areas in the western states.

Diseases that are constantly present (often at a low level) in a population within a particular geographic region are called **endemic**

diseases. For example, malaria is endemic to some regions of Brazil, but is not endemic to the United States.

Diseases for which a larger than expected number of cases occurs in a short time within a geographic region are called **epidemic diseases**. Influenza is a good example of a commonly epidemic disease. Incidence patterns of influenza tend to rise each winter in the northern hemisphere. These seasonal increases are expected, so it would not be accurate to say that influenza is epidemic every winter; however, some winters have an usually large number of seasonal influenza cases in particular regions, and such situations would qualify as epidemics (figures $15.2.e - f$).

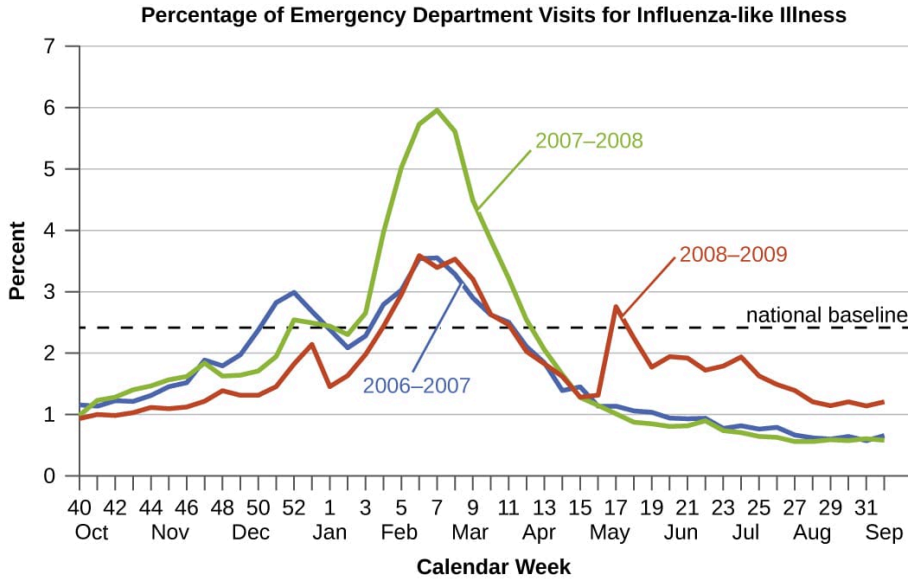


Figure $15.2.e$: The 2007–2008 influenza season in the United States saw much higher than normal numbers of visits to emergency departments for influenza-like symptoms as compared to the previous and the following years. The national baseline is near 2.5%. All years have a small peak in January and a larger peak February to April. 2007-2008 had the largest peak in February to April. 2008 – 2009 had an additional peak from May to September. (credit: modification of work by Centers for Disease Control and Prevention)

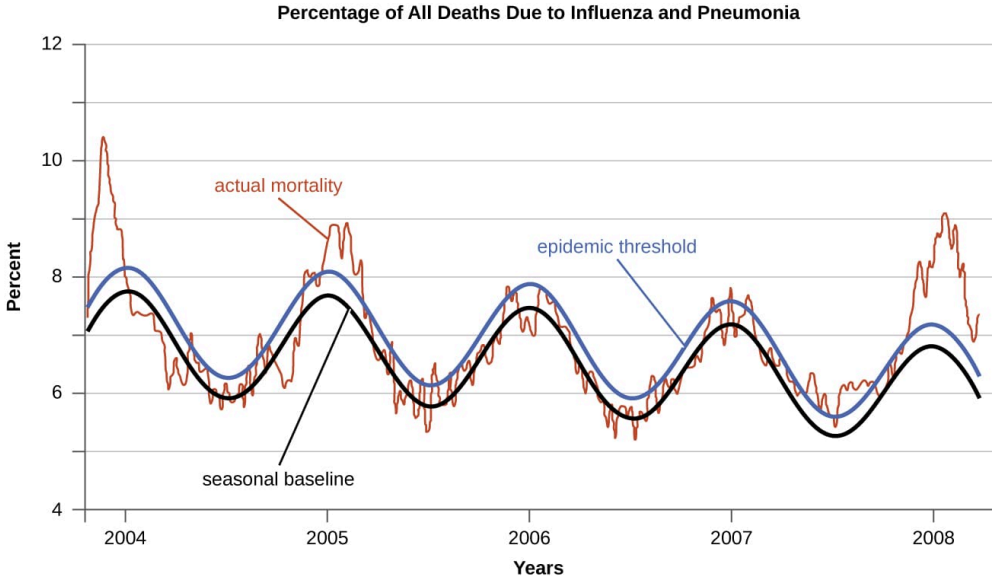


Figure $15.2.f$: The seasonal epidemic threshold (blue curve) is set by the CDC-based data from the previous five years. The seasonal baseline fluctuates to a high in winter. The epidemic threshold is just a half percent higher than the baseline. The actual mortality fluctuates above and below both of these lines. When actual mortality rates exceed this threshold, a disease is considered to be epidemic. As this graph shows, pneumonia- and influenza-related mortality saw pronounced epidemics during the winters of 2003–2004, 2005, and 2008. (credit: modification of work by Centers for Disease Control and Prevention)

An epidemic that occurs on a worldwide scale is called a **pandemic disease**. For example, HIV/AIDS (acquired immunodeficiency syndrome) and coronavirus disease 19 (COVID-19) are pandemic diseases, and novel influenza virus strains often become pandemic.

Etiology

When studying an epidemic, an epidemiologist's first task is to determinate the cause of the disease, called the etiologic agent or causative agent. Connecting a disease to a specific pathogen can be challenging because of the extra effort typically required to demonstrate direct causation as opposed to a simple association. It is not enough to observe an association between a disease and a suspected pathogen; controlled experiments are needed to eliminate other possible causes. In addition, pathogens are typically difficult to detect when there is no immediate clue as to what is causing the outbreak. Signs and symptoms of disease are also commonly nonspecific, meaning that many different agents can give rise to the same set of signs and symptoms. This complicates diagnosis even when a causative agent is familiar to scientists.

Robert Koch was the first scientist to specifically demonstrate the causative agent of a disease (anthrax) in the late 1800s. Koch developed four criteria, now known as Koch's postulates, which had to be met in order to positively link a disease with a pathogenic microbe (figure $15.2.g$). Between 1876 and 1905, many common diseases were linked with their etiologic agents, including cholera, diphtheria, gonorrhea, meningitis, plague, syphilis, tetanus, and tuberculosis. Today, we use the molecular Koch's postulates, a variation of Koch's original postulates. (You can read more about both here.)

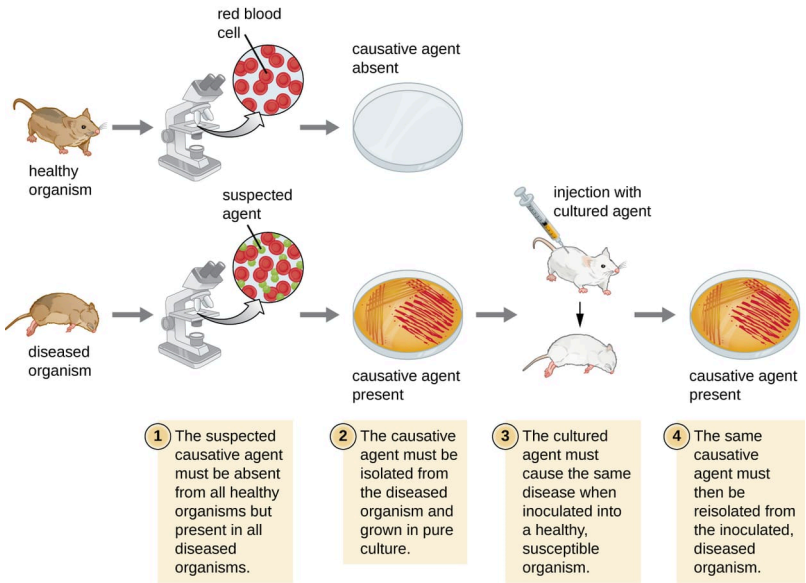


Figure $15.2.g$: The steps for confirming that a pathogen is the cause of a particular disease using Koch's postulates. (1) Only diseased organisms should contain the suspected causative agent (potential pathogen). (2) The causative agent from diseased organisms must be cultured (grown in the lab). (3) The cultured agent must then cause the same disease when a healthy, susceptible individual is infected with it (inoculated). (4) The same causative agent should be isolated and cultured from the individual in the previous step. Image and caption (modified) from OpenStax (CC-BY).

How Diseases Spread

Understanding how infectious pathogens spread is critical to preventing infectious disease. For pathogens to persist over long periods of time they require **reservoirs** where they normally reside. Reservoirs can be living organisms (rats, bats, racoons, livestock, etc.) or nonliving sites. Nonliving reservoirs can include soil and water in the environment. These may naturally harbor the organism because it may grow in that environment. These environments may also become contaminated with pathogens in human feces, pathogens shed by intermediate hosts, or pathogens contained in the remains of intermediate hosts.

An individual capable of transmitting a pathogen without displaying symptoms is referred to as a **carrier**. A **passive carrier** is contaminated with the pathogen and can mechanically transmit it to another host; however, a passive carrier is not infected. By contrast, an **active carrier** is an infected individual who can transmit the disease to others. An active carrier may or may not exhibit signs or symptoms of infection.

Regardless of the reservoir, transmission must occur for an infection to spread. **Contact transmission** includes **direct contact** or **indirect contact**. Person-to-person transmission is a form of direct contact transmission. Here the agent is transmitted by physical contact between two individuals (figure $15.2.h$) through actions such as touching, kissing, sexual intercourse, or droplet sprays. Indirect contact transmission involves inanimate objects called **fomites** that become contaminated by pathogens from

an infected individual or reservoir (figure $15.2.i$). For example, an individual with the common cold may sneeze, causing droplets to land on a fomite such as a tablecloth or carpet, or the individual may wipe her nose and then transfer mucus to a fomite such as a doorknob or towel.

Figure $15.2.h$: Direct contact transmission of pathogens can occur through physical contact. Many pathogens require contact with a mucous membrane to enter the body, but the host may transfer the pathogen from another point of contact (for example, hand) to a mucous membrane (for example, mouth or eye). (credit left: modification of work by Lisa Doehnert)

Figure $15.2.i$: Fomites are nonliving objects that facilitate the indirect transmission of pathogens. Contaminated doorknobs, towels, and syringes are all common examples of fomites. (credit left: modification of work by Kate Ter Haar; credit middle: modification of work by Vernon Swanepoel; credit right: modification of work by "Zaldylmg"/Flickr)

Vehicle transmission refers to the transmission of pathogens through vehicles such as water, food, and air. Water contamination through poor sanitation methods leads to waterborne transmission of disease. **Waterborne** disease remains a serious problem in many regions throughout the world. The World Health Organization (WHO) estimates that contaminated drinking water is responsible for more than 500,000 deaths each year. Similarly, food contaminated through poor handling or storage can lead to **foodborne** transmission of disease. Dust and fine particles known as **aerosols**, which can float in the air, can carry pathogens and facilitate the **airborne** transmission of disease.

Diseases can also be transmitted by a mechanical or biological **vector**, an animal (typically an arthropod) that carries the disease from one host to another. Ticks, fleas, and mosquitos are examples of vectors (figure $15.2.j$). **Mechanical transmission** is facilitated by a **mechanical vector**, an animal that carries a pathogen from one host to another without being infected itself. **Biological transmission** occurs when the pathogen reproduces within a **biological vector** that transmits the pathogen from one host to another (figure $15.2.k$).

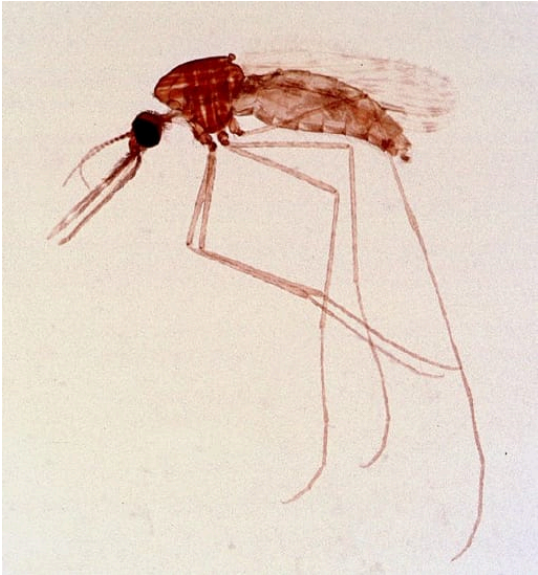
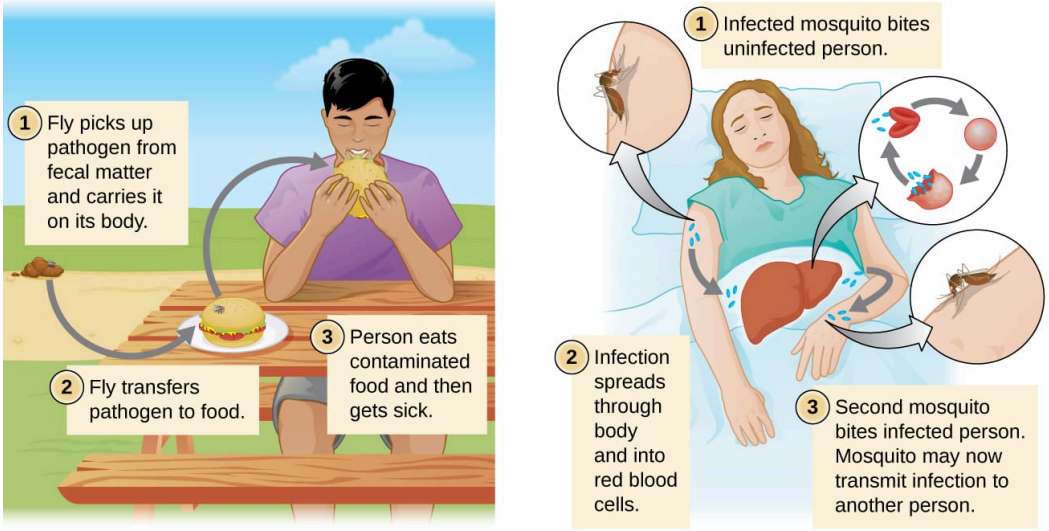


Figure $15.2.j$: The *Anopheles* mosquito is the **vector** for *Plasmodium*, which causes malaria. Image by Alan R Walker (CC-BY-SA).



(a) (b)

Figure $15.2.k$: (a) A mechanical vector carries a pathogen on its body from one host to another, not as an infection. Step 1: fly picks up pathogen from fecal matter and carries it on its body. 2: Fly transfers pathogen to food. 3: Person eats contaminated food and gets sick. (b) A biological vector carries a pathogen from one host to another after becoming infected itself. Step 1: Infected mosquito bites uninfected person. 2: Infections spreads through body and into red blood cells. 3: Second mosquito bites infected person. Mosquito may now transmit infection to another person.

Ecosystem degradation can increase disease spread through several mechanisms. First, it can promote vector populations. For example, deforestation, dams, and urbanization increase the amount of standing water, increasing habitat for vectors, such as mosquitoes. Additionally, climate change may expand the range of disease vectors that are limited to tropical or subtropical regions. Second, disruptions in the water cycle can create conditions that favor pathogens. For example, fertilizer runoff from agriculture increases nutrient levels, making bodies of water more suitable for the bacterium that causes cholera. Increased flooding as a result of changes in land use and climate change also facilitates the spread of waterborne disease.

A third way that ecosystem degradation can increase disease spread is through decreasing biodiversity. For example, Lyme disease is caused by the bacterium *Borrelia* and is transmitted to humans from small mammals (the reservoirs) by ticks (figures $15.2.l - m$). Some reservoirs (squirrels and opossums) remove ticks, reducing infection, but field mice do not. Habitat fragmentation has increased field mice relative to squirrels and opossums and thus increased the reservoir for Lyme disease.

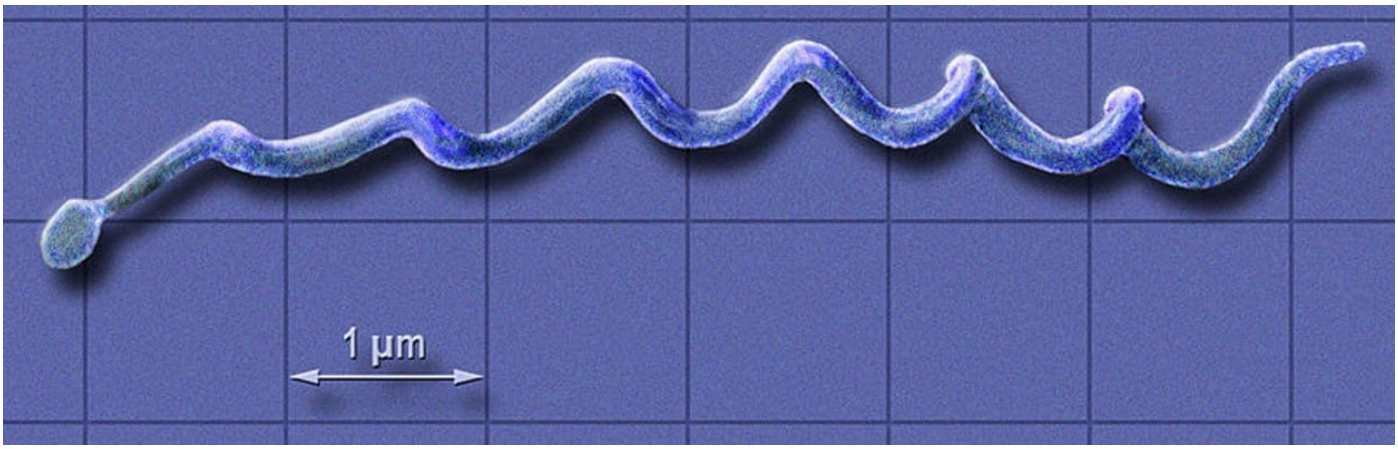


Figure $15.2.l$: Drawing of the bacterium *Borrelia burgdorferi*, which causes Lyme disease. Image by Lamiot (CC-BY-SA).

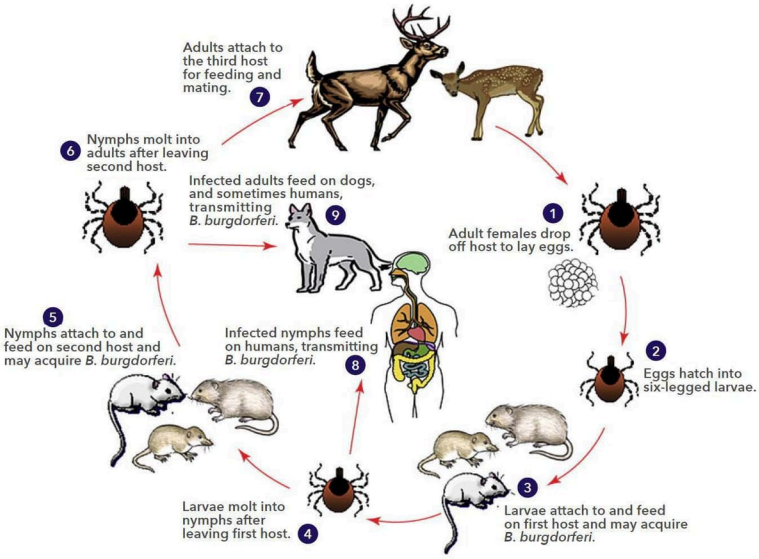


Figure $15.2.m$: Life cycle of the bacterium *Borrelia burgdorferi*, which causes Lyme disease. Ticks can acquire this bacterium when the feed on the initial host and then transmit the disease to humans. Step 1: Adult females drop off host to lay eggs. 2: Eggs hatch into six-legged larvae. 3: Larvae attach to and feed on first host (various small mammals) and may acquire *B. burgdorferi*. 4: Larvae molt into nymphs after leaving first host. 5: Nymphs attach to and feed on second host and may acquire *B. burgdorferi*. 6: Nymphs molt into adults after leaving second host. 7: Adults attach to the third host (such as deer) for feeding and mating. 8: An arrow branches from step 4 indicating that infected nymphs feed on humans, transmitting *B. burgdorferi*. 9: Infected adults feed on dogs and sometimes humans, transmitting *B. burgdorferi*. Image from Tick-Borne Disease Working Group 2018 Report to Congress.

Individuals suspected or known to have been exposed to certain contagious pathogens may be **quarantined**, or isolated to prevent transmission of the disease to others. Hospitals and other health-care facilities generally set up special wards to isolate patients with particularly hazardous diseases such as tuberculosis or COVID-19 (figure $15.2.n$). Depending on the setting, these wards may be equipped with special air-handling methods, and personnel may implement special protocols to limit the risk of transmission, such as personal protective equipment or the use of chemical disinfectant sprays upon entry and exit of medical personnel.

(a) (b)

Figure $15.2.n$: (a) The Aeromedical Biological Containment System (ABCS) is a module designed by the CDC and Department of Defense specifically for transporting highly contagious patients by air. (b) An isolation ward for Ebola patients in Lagos, Nigeria. (credit a: modification of work by Centers for Disease Control and Prevention; credit b: modification of work by CDC Global)

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15.3: Infectious Diseases

Worldwide, infectious diseases (biological hazards) accounted for three of the 10 leading causes of death in 2020. In children under five leading causes of death include acute respiratory infections (from indoor air pollution); diarrheal diseases (mostly from poor water, sanitation, and hygiene); and other 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. For example, 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.

An **emerging infectious disease** is either new to the human population or has shown an increase in prevalence in the previous twenty years. Examples include coronavirus disease 19 (COVID-19), Ebola virus disease, West Nile virus, Zika virus, sudden acute respiratory syndrome (SARS), H1N1 influenza; swine and avian influenza (swine, bird flu), human immunodeficiency virus (HIV)/acquired immunodeficiency syndrome (AIDs), and a variety of other viral, bacterial, and protozoal diseases (table $15.3.a$). Whether the disease is new or conditions have changed to cause an increase in frequency, its status as emerging implies the need to apply resources to understand and control its growing impact. Emerging diseases may change their frequency gradually over time, or they may experience sudden widespread growth.

Table $15.3.a$***:*** *Some Emerging and Reemerging Infectious Diseases*

Disease	Pathogen	Year Discovered	Affected Regions	Transmission
AIDS	HIV	1981	Worldwide	Contact with infected body fluids
Chikungunya fever	Chikungunya virus	1952	Africa, Asia, India; spreading to Europe and the Americas	Mosquito-borne
Ebola virus disease	Ebola virus	1976	Central and Western Africa	Contact with infected body fluids
H1N1 Influenza (swine flu)	H1N1 virus	2009	Worldwide	Droplet transmission
Lyme disease	*Borrelia burgdorferi* bacterium	1981	Northern hemisphere	From mammal reservoirs to humans by tick vectors
West Nile virus disease	West Nile virus	1937	Africa, Australia, Canada to Venezuela, Europe, Middle East, Western Asia	Mosquito-borne

Emerging diseases are found in all countries, both developed and developing. Some nations are better equipped to deal with them. National and international public health agencies watch for epidemics in developing countries because those countries rarely have the health-care infrastructure and expertise to deal with large outbreaks effectively. In addition to the altruistic goal of saving lives and assisting nations lacking in resources, the global nature of transportation means that an outbreak anywhere can spread quickly to every corner of the planet. Managing an epidemic in one location—its source—is far easier than fighting it on many fronts.

In 2015, the WHO set priorities on several emerging diseases that had a high probability of causing epidemics and that were poorly understood (and thus urgently required research and development efforts).

A **reemerging infectious disease** is a disease that is increasing in frequency after a previous period of decline. Its reemergence may be a result of changing conditions or old prevention regimes that are no longer working. Examples of such diseases are drug-resistant forms of tuberculosis, bacterial pneumonia, and malaria. Drug-resistant strains of the bacteria causing gonorrhea and syphilis are also becoming more widespread, raising concerns of untreatable infections.

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.

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.

Selected Infectious Diseases

COVID-19

Coronavirus disease 19 (**COVID-19**) is a respiratory illness caused by a virus called novel species of coronavirus (SARS-CoV-2). Symptoms include fever or chills, cough, shortness or breath or difficulty breathing, fatigue, headache, and sore throat. The WHO declared coronavirus disease 19 (COVID-19) a public health emergency of international concern on January 30 and a pandemic on March 11, 2020. A seemingly limited cluster of cases of pneumonia linked to a sea food market in Wuhan, China has become one of the worst pandemics in human history with a staggering number of more than 90.2 million infections in 177 countries and 1.9 million deaths globally as of January 10, 2021 (figure $15.3.a$). This illustrates how locally emerging pathogens have the capacity to spread rapidly and cross borders and become an imminent public health threat to the entire world. You can view the the latest COVID-19 data here.

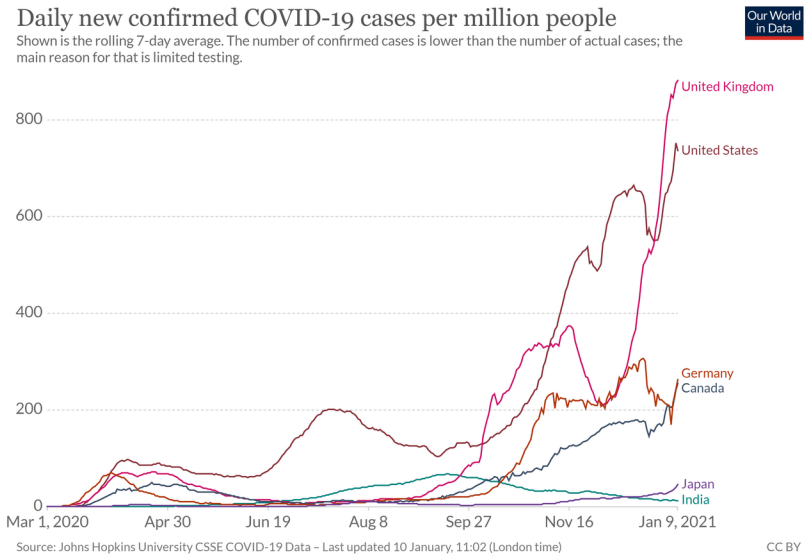

Figure $15.3.a$: New confirmed COVID-19 cases per million people from March 1, 2020 to Junuary 10, 2021 in selected countries. Image by Max Roser, Hannah Ritchie, Esteban Ortiz-Ospina and Joe Hasell (2020) - "Coronavirus Pandemic (COVID-19)". Published online at OurWorldInData.org. (CC-BY).

Studies indicate that SARS-CoV-2 might originate from bat coronaviruses and infects humans directly or through other animals as intermediaries. It primarily spreads between humans through the respiratory tract by involving droplets, aerosols, respiratory secretions, or saliva. It is most often spread by direct contact transmission, but it airborne transmission has been documented in certain situations, such as in an enclosed space (figure $15.3.b$). Researchers continue to investigate airborne transmission of the virus. This coronavirus is infectious during its incubation period, which is reported to be 3-7 days, at most 14 days, when

no symptoms are shown in patients. Those infected may experience mild to moderate disease (80%), severe disease (15%), and critical illness (5%) with an overall case fatality rate of 0.5–2.8% with much higher rates (3.7–14.8%) in octogenarians. The severe and critical illness categories (about 20% of all infections) have overwhelmed health systems worldwide (figure $15.3.c$). The Centers for Disease Control and Prevention's COVID-19 page has the latest information about preventing transmission, vaccines, symptoms, and testing.

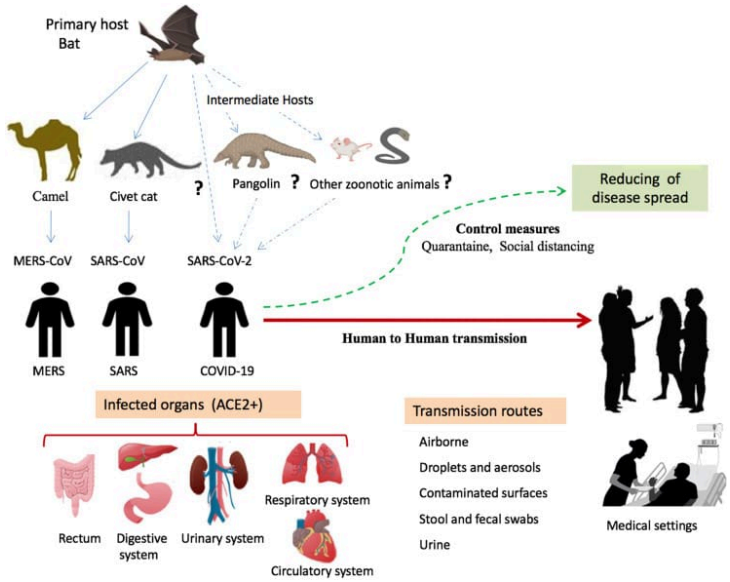

Figure $15.3.b$: Origin of SARS-CoV-2 and potential transmission routes to humans. SARS-CoV-2 transmitted to humans from bats directly or by intermediate hosts such as rats, pangolins, snakes, and rats. The virus is spread among humans by different routes including droplets, aerosols, direct contact, and other potential routes such as urine, stool, and fecal swabs. Human organs with a protein called the ACE2 receptor (ACE2+) are targets for viral infection. Disease spread can be limited through quarantining when sick, social distancing, avoiding large gatherings (not shown), wearing masks (not shown), and vaccinations (not shown). Image and caption (modified) from Tizaoui, K., Zidi, I., Lee, K. H., Ghayda, R. A., Hong, S. H., Li, H., Smith, L., Koyanagi, A., Jacob, L., Kronbichler, A., & Shin, J. I. (2020). Update of the current knowledge on genetics, evolution, immunopathogenesis, and transmission for coronavirus disease 19 (COVID-19). *International journal of biological sciences*, *16*(15), 2906–2923. https://doi.org/10.7150/ijbs.48812 (CC-BY).

Figure $15.3.c$: Lieutenant (junior grade) Natasha McClinton, a surgical nurse, prepares a patient for a procedure in the intensive care unit aboard the U.S. hospital ship USNS Comfort. The ship cares for critical and non-critical patients without regard to their COVID-19 status. In April of 2020, Comfort worked with Javits New York Medical Station as an integrated system to relieve the New York City medical system as a response to the COVID-19 pandemic. Image and caption (modified) from US Navy Mass Communication Specialist 2nd Class Sara Eshleman (public domain).

Ebola Virus Disease

Ebola virus disease, previously known as Ebola hemorrhagic fever, is a rare and deadly disease caused by infection with one of the Ebola virus strains (figure $15.3.d$). Ebola can cause disease in humans and nonhuman primates. Health experts had been aware of the Ebola virus since the 1970s, but outbreak at scale that had not yet been seen occurred in western Africa through 2014–2016. Previous human epidemics had been small, isolated, and contained. Indeed, the gorilla and chimpanzee populations of western Africa had suffered far worse from Ebola than the human population. The pattern of small isolated human epidemics changed in 2014. Its high transmission rate, coupled with cultural practices for treatment of the dead and perhaps its emergence in an urban setting, caused the disease to spread rapidly, and thousands of people died. The international public health community responded with a large emergency effort to treat patients and contain the epidemic.

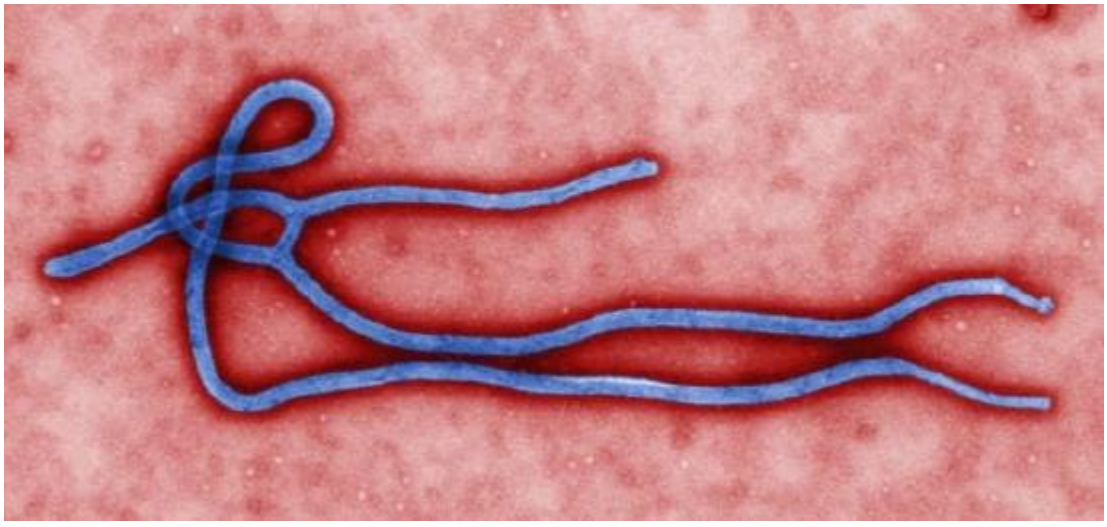

Figure $15.3.d$: The Ebola virus. Image by CDC (public domain).

The 2014-2016 Ebola epidemic was the largest in history (with 28,616 cases and 11,310 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. Even with the support of international agencies, the systems in western Africa struggled to identify and care for the sick and control spread. Engaging local leaders in prevention programs and messaging, along with careful policy implementation at the national and global level, helped to eventually contain the spread of the virus and put an end to this outbreak. The U.S. Food and Drug Administration approved a vaccine for Ebola late in 2019.

HIV/AIDS

Human immunodeficiency virus (**HIV**) is a virus that attacks the body's immune system. If HIV is not treated, it can lead to **acquired immunodeficiency syndrome** (**AIDS**). Those with AIDS have weakened immune systems and are thus more susceptible to cancers and other infections. First identified in 1981, the **HIV/AIDS** epidemic has spread with ferocious speed. In 2019, 38 million people were living HIV globally. Over 95 percent of people living with HIV are in low- and middle- income countries. There were 1.7 million new infections in 2019, and more than half of new infections are among young people below age 25. In 2019 alone, 690,000 million people died from AIDS and related illnesses. In 2016, HIV/AIDS is was the second leading cause of death in Africa. At its peak, the epidemic cut life expectancy by more than 10 years in several nations (figure $15.3.e$).

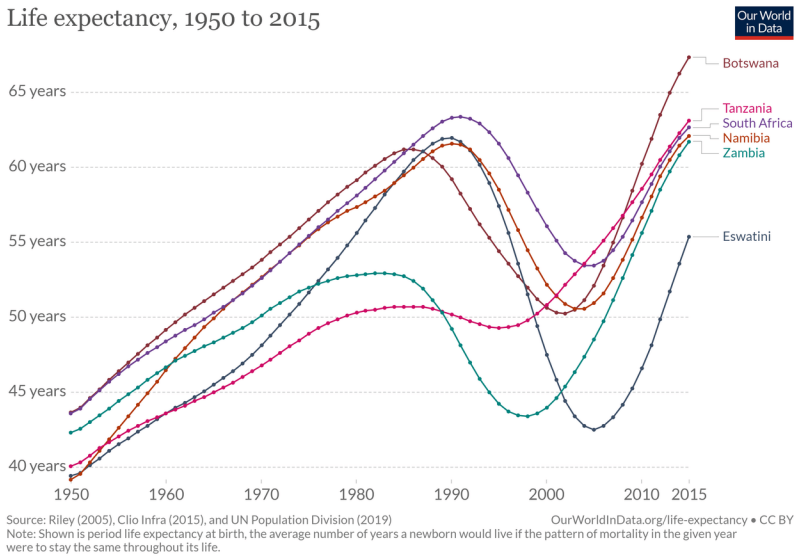

Figure $15.3.e$: Life expectancy in six countries in Sub-Saharan Africa dropped dramatically in the late 1990s and early 2000s. As the efforts to control the pandemic reduced the number of new infections (incidence) and death rates from HIV, life expectancy has again increased. Image by Max Roser and Hannah Ritchie (2018) - "HIV / AIDS". Published online at OurWorldInData.org. (CC-BY).

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 protozoan parasite called *Plasmodium*. There were 229 million cases of malaria and 409,000 deaths in 2019 with most cases and deaths found in Sub-Saharan Africa (**figure** $15.3.f$ **).** 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 (lack of sufficient red blood cells to deliver oxygen) 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.

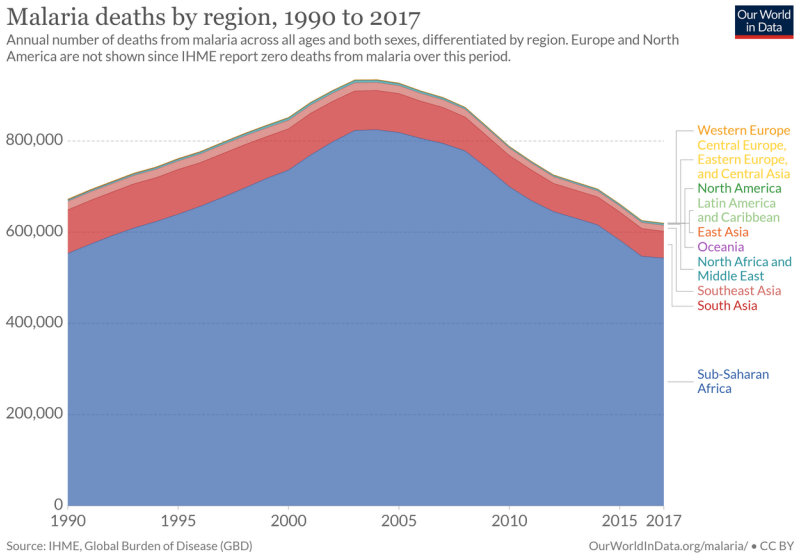

Figure $15.3.f$: Deaths caused by malaria from 1990 to 2017. Deaths peaked above 800,000 around 2004 and were just above 600,000 in 2017. The largest share of deaths occurred in Sub-Saharan Africa. Image by Max Roser and Hannah Ritchie (2013) - "Malaria". Published online at OurWorldInData.org. (CC-BY).

Tuberculosis

The WHO estimates that 10.4 million new cases and 1.5 million deaths occur from **tuberculosis** (**TB**) each year. One-third of TB cases remain unknown to the health care system. For those accessing treatment, however, prevalence and mortality have declined significantly, and millions of lives have been saved.

Tuberculosis is caused by the bacterium *Mycobacterium tuberculosis*, which is transmitted between humans through the respiratory route and most commonly affects the lungs but can damage any tissue. When an infected individual coughs, exhales, speaks, etc., the bacterium is released in droplets that can remain suspended in the air for several hours. Only a minority (approximately 10 percent) of individuals infected with *M. tuberculosis* progress to active TB disease, while the remainder may maintain a latent infection that serves as a reservoir. TB has special challenges, including (a) a substantial number of patients with active disease are asymptomatic, capable of transmitting infection without knowing it; (b) patients must maintain compliance with treatment for six to nine months; and (c) the pathogen persists in many infected individuals in a latent state for many years but can be reactivated over a lifetime to cause disease and become transmissible.

This video by the CDC explains the basics of TB.

YouTube Video

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Disease Eradication

Many diseases have been eradicated or are nearly eradicated worldwide (Table $15.3.b$). Strategies to eradicate disease infectious diseases include vaccination, improved hygiene and sanitation, preventative medication, and public health education. Some of these strategies are discussed in Environmental Health Reduction, and vaccination is discussed below.

Table $15.3.b$***:*** *Infectious diseases that have been eradicated and could be eradicated in the future.*

Disease	Burden of disease	Cause	Ways to eradicate	Fatality
Smallpox	Declared eradicated in 1980	Variola virus	Eradicated using vaccination	30%
Rinderpest	Declared eradicated in 2011	Rinderpest virus	Sanitary measures and vaccination	100%
Poliomielitis	116 cases in 2017	Poliovirus	Vaccination	For paralytic polio 2-5% in children and increases to 15-30% in adults
Guinea worm disease	30 cases in 2017	Parasitic worm *Dracunculus medinensis*	Hygiene, water decontamination and health education	Not fatal but debilitating
Measles	173,457 reported cases to WHO in 2017	Measles morbillivirus	Vaccination	15%
Mumps	560,622 reported cases to WHO in 2017	Mumps orthorubulavirus	Vaccination	0.01% for mumps-caused encephalitis
Rubella	6,789 reported cases to WHO in 2017	Rubella virus	Vaccination	Not reported

Disease	Burden of disease	Cause	Ways to eradicate	Fatality
Lymphatic filariasis	No estimate available. In 2014, 68 million people were infected and 790 million people where at risk of infection	Roundworms: *W. bancrofti, B. malayi, B. timori*	Preventive chemotherapy	Not fatal but highly debilitating
Cysticercosis	2.56–8.30 million cases estimated by the WHO	Tapeworms: *T. solium, T. saginata, T. asiatica*	Sanitation and health education. Vaccination of pigs	Varies between countries <1-30%

Table modified from Max Roser, Sophie Ochmann, Hannah Behrens, Hannah Ritchie and Bernadeta Dadonaite (2014) - "Eradication of Diseases". Published online at OurWorldInData.org. (CC-BY).

Vaccination

Vaccines function in inducing a specific immune response that can immediately counter a pathogen if exposed. Vaccines lead to the production of specialized cells and antibodies, which can efficiently and effectively target pathogens. There are several types of vaccines. Some consists of dead or inactivated pathogens or parts of them. The Pfizer-BioNTech and Moderna COVID-19 vaccines, approved by the FDA in December of 2020 consist of a piece of the the virus's genetic material (called mRNA). When injected, the body uses this genetic information to synthesize the spike protein of the virus, which stimulates an immune responses without causing infection.

Development and approval of a vaccine does not automatically eradicate a disease (figure $15.3.g$), for the vaccine must be distributed to those who need it. Access is particularly challenging in developing countries, especially for low-income individuals there. In the case of tuberculosis, which remains widespread, a vaccine has been available for 100 years, but it is more effective in protecting severe forms of the disease in children than lung infections in adults. A new, more effective vaccine is likely needed to eradicate tuberculosis.

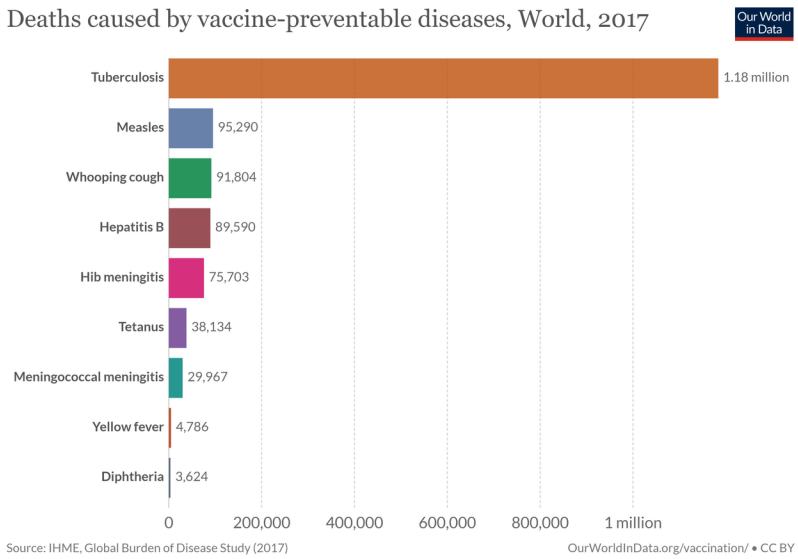

Figure $15.3.g$: Global deaths in 2017 that were caused by diseases with existing vaccines. Tuberculosis was responsible for 1.18 million deaths followed by measles (95,290), whooping cough (91,804), hepatitis B (85,590), Hib meningitis (75,703), tetanus (38,134), meningococcal meningitis (29,967), yellow fever (4,786), and diphtheria (3,624). Image by Samantha Vanderslott and Bernadeta Dadonaite (2013) "Vaccination". Published online at OurWorldInData.org. (CC-BY).

New vaccines must be rigorously tested before they are approved. Not only are vaccines safe, but we would face spikes in deadly infectious diseases without them. The antivax movement has unfortunately spread false information questioning the safety of vaccines, but you can educate yourself with reliable information about the development, testing, and safety of vaccines here.

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. Technically, **antibiotics** are substances that are produced by certain microorganisms (such as the fungus, *Penicillium*, or the bacterium *Streptomyces*) that inhibit the growth of other microorganisms. However, any drugs used to treat bacterial infections are commonly referred to as antibiotics. Neither of these definitions includes substances used to treat viral infections, which are called antivirals. Since the 1940s, the use of antiobitics has 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.

Overuse of antibiotics have allowed pathogens to evolve **antibiotic resistance**, which occurs when bacteria change in a way that reduces the effectiveness of drugs, chemicals, or other agents designed to cure or prevent infections (figure $15.3.h$). Overuse takes many forms, such as the inclusion of antibiotics in household products or prescribing antibiotics to treat infections without first determining whether the infection is bacterial or viral (in which case, the antibiotic would not be effective). Similar to the evolution of pesticide resistance, widespread use of antibiotics favors individuals that happen to have gene versions conferring antibiotic resistance. These individuals have the best chance of surviving and reproducing, so much so, that an antibiotic-resistant strain evolves. The initial antibiotic is not longer effective against this strain, and it must be treated with alternative medications. For example, tuberculosis (TB) was nearly eliminated in most parts of the world, but drug-resistant strains have now reversed that trend.

A similar example of drug resistance has evolved in *Plasmodium*, the protozoa that cause malaria. The insecticide dichlorodiphenyltrichloroethane (DDT) 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 *Plasmodium* to become drug-resistant.

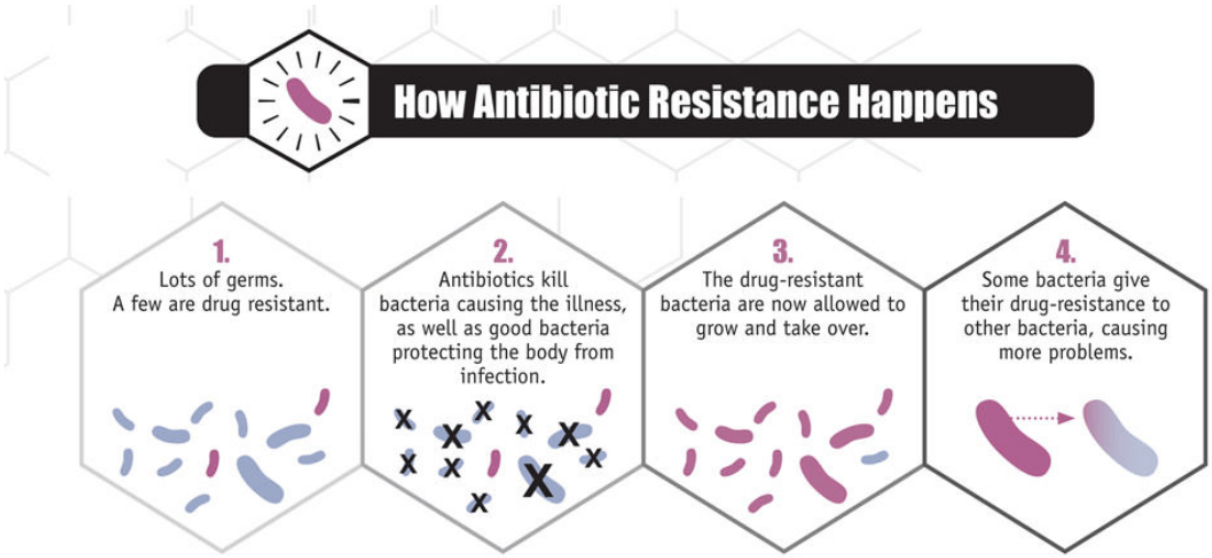

Figure $15.3.h$: Antibiotic resistance is of increasing concern to medical professionals. (1) Initially, a variety of microbes (germs) are present, and a few are drug resistant. (2) When antibiotics are used, they kill both disease-causing microbes and beneficial ones. However, drug-resistant microbes remain. (3) The drug-resistant microbes multiple and can eventually produce a drug-resistant strain. (4) Drug-resistant bacteria can even pass their resistance genes to other bacteria, including those of different species.

New forms of antibiotic resistance can cross international boundaries and spread between continents with ease. Many forms of resistance spread with remarkable speed. Each year in the United States, at least 2 million people acquire serious infections with bacteria that are resistant to one or more of the antibiotics designed to treat those infections. At least 23,000 people die each year in the US as a direct result of these antibiotic-resistant infections. Many more die from other conditions that were complicated by an antibiotic-resistant infection. The use of antibiotics is the single most important factor leading to antibiotic resistance around the world. Antibiotics are among the most commonly prescribed drugs used in human medicine, but up to 50% of all the antibiotics prescribed for people are not needed or are not optimally effective as prescribed.

The video below shows an experiment done at Harvard Medical school, where they show bacteria adapting very quickly to apparently deadly conditions.

YouTube Video

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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.

Attribution

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- Balkhair A. A. 2020. COVID-19 Pandemic: A New Chapter in the History of Infectious Diseases. *Oman medical journal*, *35*(2), e123. https://doi.org/10.5001/omj.2020.41 (CC-BY-NC).
- Tizaoui, K., Zidi, I., Lee, K. H., Ghayda, R. A., Hong, S. H., Li, H., Smith, L., Koyanagi, A., Jacob, L., Kronbichler, A., & Shin, J. I. (2020). Update of the current knowledge on genetics, evolution, immunopathogenesis, and transmission for coronavirus disease 19 (COVID-19). *International journal of biological sciences*, *16*(15), 2906–2923. https://doi.org/10.7150/ijbs.48812 (CC-BY).
- Ebola (Ebola Virus Disease). 2020. Centers for Disease Control and Prevention. Accessed 10 January 2021. (public domain)
- 2014-2016 Ebola Outbreak in West Africa. 2019. Centers for Disease Control and Prevention. Accessed 10 January 2021. (public domain)
- About HIV. 2020. Centers for Disease Control and Prevention. Accessed 10 January 2021. (public domain)
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15.4: Environmental Toxicology

Environmental toxicology is the scientific study of the properties of **toxins**, chemicals that may cause damage to living organisms, and the health effects associated exposure to them (table $15.4.a$). The field also involves managing these toxins and the protecting humans and ecosystems from them. **Toxicologists** are scientists who study the properties of toxins, and these damage-causing properties, are called **toxicity**. In other words, toxicologists evaluate chemical hazards.

Table $15.4.a$***:*** *The 15 Highest Priority Toxins According to the Agency for Toxic Substances and Disease Registry (ATSDR) Substance Priority List in 2019. These substances are ranked based on their toxicity and chance of exposure at sites on the National Priorities List (NPL), where toxins have been spilled or otherwise released.*

2019 Rank	Substance Name
1	Arsenic
2	Lead
3	Mercury
4	Vinyl chloride
5	Polychlorinated biphenyls (PCBs)
6	Benzene
7	Cadmium
8	Benzo[a]pyrene
9	Polycyclic aromatic hydrocarbons
10	Benzo[b]fluoranthene
11	Chloroform
12	Aroclor 1260
13	p,p'-DDT
14	Aroclor 1254
15	Dibenz[a,h]anthracene

Table modified from ATSDR/CDC (public domain).

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 (figure $15.4.a$). 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.

Figure $15.4.a$: Crystals of benzene under a layer of liquid benzene. They were formed inside a container exposed to temperatures below 5.5°C. Their smoothness is the result of taking the photograph some time after bringing the container inside an atmosphere at room temperature, where they began to melt. Image and caption by Endimion17 (CC-BY-SA).

Routes of Exposure to Chemicals

In order to cause health problems, chemicals must enter your body. 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. There are three main **routes of exposure**, or ways a chemical can get into your body (figure $15.4.b$).

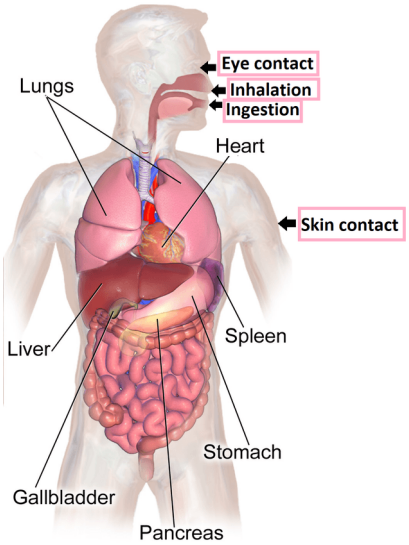

Figure $15.4.b$: The routes of exposure through which toxins can enter the body (inhalation, ingestion, and skin or eye contact) are boxed in pink. Image by BruceBlaus (CC-BY-SA).

The first route is **inhalation**, which results from breathing in chemical gases, mists, or dusts that are in the air. Because the air sacs in the lungs are structure for gas exchange, consisting of only a single layer of thin cells, inhaled substances can rapidly pass from the air sacs into capillaries and enter the bloodstream. Inhaled toxins can also cause local damage to the mouth, airways, and lungs.

The second route is **ingestion**, swallowing that occurs when chemicals have spilled or settled onto food, beverages, cigarettes, beards, or hands. Toxins can then cause local damage to the digestive tract and may be absorbed, most often through the

intestines, into the blood stream.

The third route is **skin or eye contact**. When chemicals directly touch the skin or get in the eyes, they can cause localized damage or be absorbed through the skin into the bloodstream. Because the skin consists of many cell layers that are reinforced with protective compounds, it is more difficult for toxins to enter the body through the skin compared to inhalation and ingestion. However, toxins can easily enter through damaged skin, and some substances can be absorbed through intact skin. Because the eyes have a rich blood supply, toxins can ready enter the bloodstream through eye contact.

What Factors Impact a Chemical's Safety?

Why are some chemicals more harmful than other? Many factors are considered when evaluating a chemical's safety including potency, persistence, solubility, bioaccumulation and biomagnification. **Potency** refers to the amount of a chemical needed to cause harm. The more potent a toxin, the lower the concentration needed to cause harm. **Persistence** refers to how long a substance takes to break down. Persistent chemicals are of greater concern because they remain in the environment (or even in organisms) for long time periods. **Solubility** refers to whether the chemical dissolves in certain solvents, such as water or fat. Generally, fat-soluble (lipid-soluble) toxins are more dangerous because they can accumulate in fatty tissues (see below) whereas water-soluble toxins could be more easily flushed out of the body. Furthermore, fat-soluble toxins are more easily absorbed by the body.

Bioaccumulation

Bioaccumulation is the buildup of chemicals in an organism's tissues over its lifetime. While bioaccumulated toxins are commonly fat soluble, such as DDT and PCBs, water-soluble toxins, such as inorganic forms of heavy metals can also bioaccumulate. For example, lead accumulates in the teeth and bone, and mercury can accumulate in the kidneys and brain.

Biomagnification

Biomagnification is the increasing concentration of toxins in organisms at each successive trophic level. When organisms with bioaccumulated toxins are consumed, the toxins are transferred to their predators (figure $15.4.d$). Biomagnification explains why some fish species high on the food chain contain high concentrations of mercury and cadmium, another heavy metal.

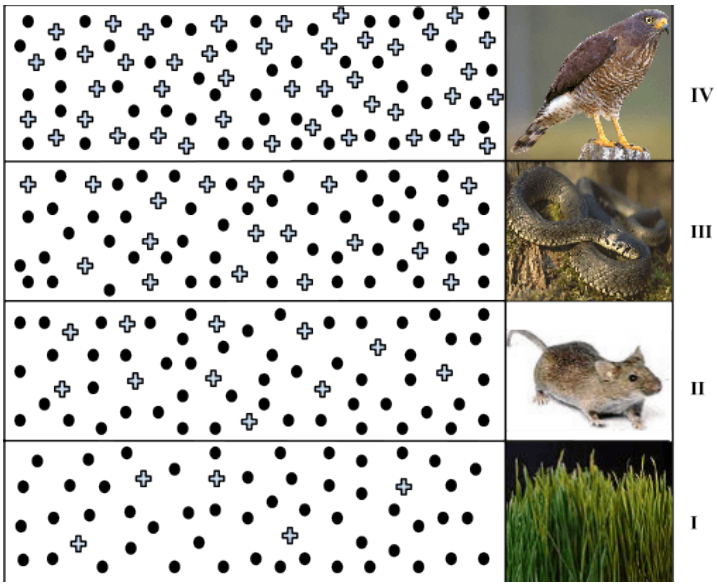

Figure $15.4.c$: Biomagnification. The biomagnified toxin becomes concentrated in the tissues of organisms representing four successive trophic levels in a food chain. Most of the toxin absorbed by primary producers remains in their bodies at that first trophic level. Through biomagnification, the concentration of the toxin (crosses) increases higher up the food chain. (Black dots represent other molecules.) Organisms at the top thus have a higher tissue concentration of toxins than lower levels. Trophic level I represents the primary producers; trophic level II represents the primary consumers; trophic level III represents the secondary consumers; and trophic level IV represents the tertiary consumers. Image by Sballesteros15 (CC-BY-SA).

In addition to high persistence, fat solubility, and bioaccumulation, biomagnification explains why the now-banned insecticide dichlorodiphenyltrichloroethane (DDT) caused so much damage. Producers absorbed DDT and passed it on to successive levels of consumers at increasingly higher rates. For example, spraying a marsh to control mosquitoes will cause trace amounts of DDT to accumulate in the cells of microscopic aquatic organisms, the plankton, in the marsh. In feeding on the plankton, filter-feeders, like clams and some fish, harvest DDT as well as food. (Concentrations of DDT 10 times greater than those in the plankton have been measured in clams.) The process of concentration goes right on up the food chain from one trophic level to the next. Gulls, which feed on clams, may accumulate DDT to 40 or more times the concentration in their prey. This represents a 400-fold increase in concentration along the length of this short food chain. Ultimately, apex predators at the top of the food chain such as Bald Eagles, pelicans, falcons, and ospreys fed on contaminated fish, reaching dangerous DDT levels.

Another substances that biomagnifies is polychlorinated biphenyl (PCB). The National Atmospheric and Oceanic Administration (NOAA) studied biomagnification of PCB in the Saginaw Bay of Lake Huron of the North American Great Lakes (figure $15.4.d$). Concentrations of PCB increased from the producers of the ecosystem (phytoplankton) through the different trophic levels of fish species. The apex predator, the walleye, had 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. This aquatic ecosystem offered an ideal opportunity to study biomagnification because PCB generally exists at low concentrations in this environment, but apex predators accumulated very high concentrations of the toxin.

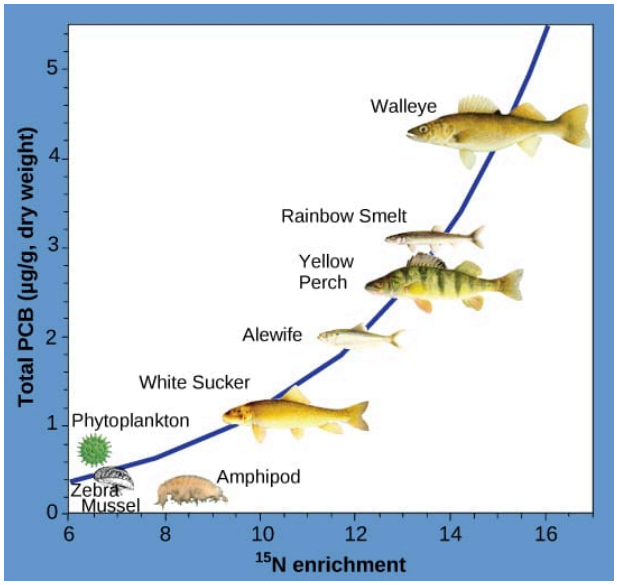

Figure $15.4.d$: Polychlorinated biphenyl (PCB) concentrations found at the various trophic levels in the Saginaw Bay ecosystem of Lake Huron. Numbers on the x-axis reflect enrichment with heavy isotopes of nitrogen (^{15}N), which is a marker for increasing trophic level. Notice that the fish in the higher trophic levels accumulate more PCBs than those in lower trophic levels. The organisms in order of ^{15}nitrogen enrichment are phytoplankton, zebra mussel, amphipod, white sucker, alewife, yellow perch, rainbow smelt, and walleye. (credit: Patricia Van Hoof, NOAA, GLERL)

Persistent Organic Pollutants (POPs)

Persistent organic pollutants (POPs) are a group of organic chemicals that pose risks to human health and ecosystems. Examples include the pesticide dichlorodiphenyltrichloroethane (DDT) and the industrial chemicals polychlorinated biphenyls (PCBs) and per- and polyfluoroalkyl substances (PFAS). The contaminant in Agent Orange (2,3,7,8-tetrachlorodibenzo-p-dioxin; TCDD) is another POP (see The Scientific Method). Persistent organic pollutants 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 (for example, 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.

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**).

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.

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 biomagnify at each level of the food chain, top predators, including whales, seals, polar bears, birds of prey, tuna, swordfish and bass may have a million times greater concentrations of POPs than the water itself. 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.

While generally banned or restricted (figure $15.4.e$), 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 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.

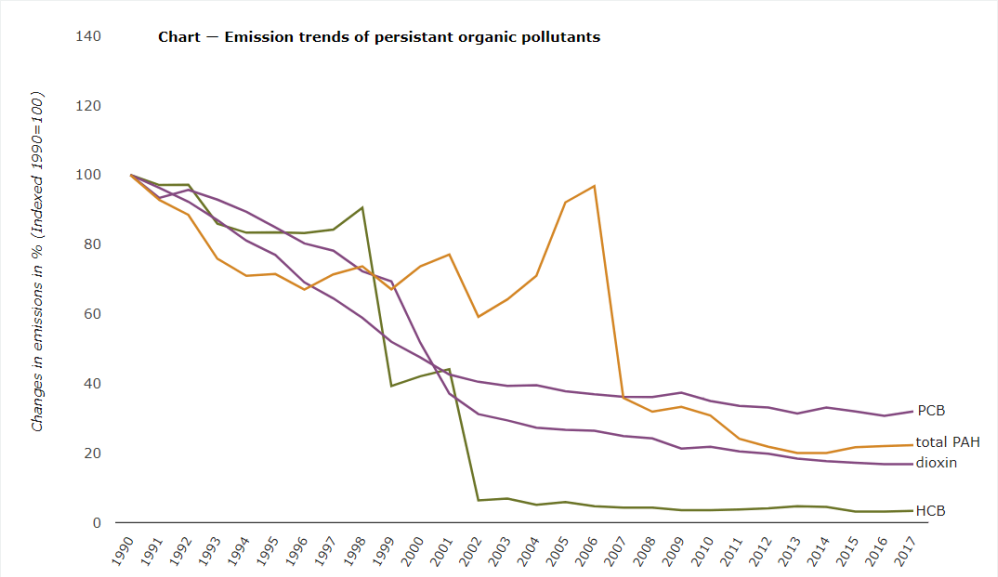

Figure $15.4.e$: Emissions of several persistent organic pollutants (POPs) by European Union countries has decreased over the years. These include hexchlorobenze (HCB), polychlorinated biphenyls (PCBs), dioxins (such TCDD), and total polycyclic aromatic hydrocarbons (PAHs), However, these compounds remain in the environment for long periods of time. Image modified from European Environment Agency of the European Union (CC-BY)

What Are the Health Effects of Toxins?

A toxin's effect is determined by many factors. Firstly, the same toxin and the same concentration can affect individuals differently depending on age, overall health, genetics, gender, and other factors. For example, young children are especially susceptible to heavy metals and bisphenol A (BPA). Additionally, as many toxins are processed by the liver, and liver function decreases with age, elderly individuals are more susceptible to certain toxins. Similarly, an generally health individual is likely to withstand exposure toxins better than someone facing other health concerns. Regarding genetics, some individuals may have versions of genes that make them more susceptible or resistant to certain toxins. In addition to individual factors, the length of exposure, presence of other toxins, and concentration (dosage) all impact toxicity

Acute vs. Chronic Effects

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

Toxicological Interactions

Exposure to multiple chemicals simultaneously can result in a variety of effects, or **chemical interactions** (figure $15.4.f$). These can apply to any chemicals that affect the body, including drugs and toxins (in the latter case, they are called **toxicological interactions**.) If the effect of the two chemicals combined is the sum of their individual effects, the chemical interaction is called an **additive effect**. Suppose that drug A and drug B have the same effect on the body (for example, each increasing heart rate by five beats per minute). An additive effect would occur if taking both drugs together increased the heart rate by 10 beats per minute. For example, toluene and xylene, which are both found in solvents and paints have an additive effect. Each causes eye, nose, and throat irritation, dizziness, headaches, and confusion. A study found that their combined effects on memory, cognitive function, and coordination was roughly equal to the sum of their individual effects.

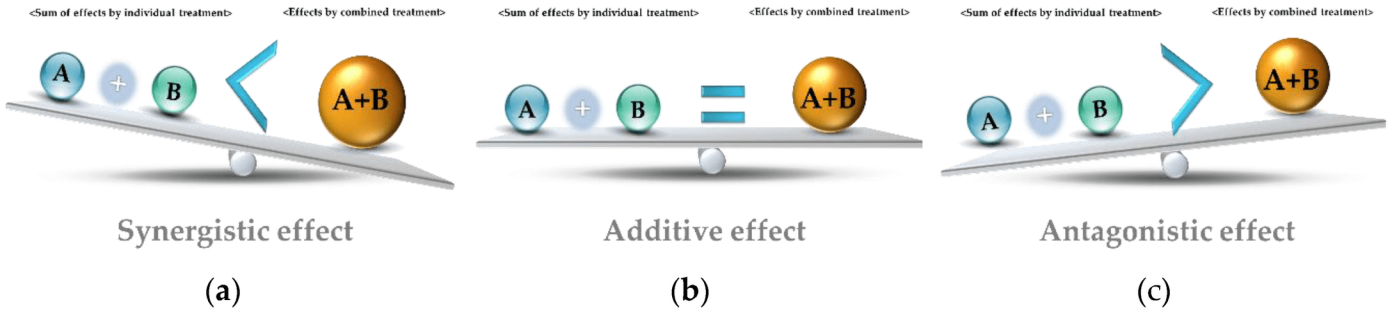

Figure $15.4.f$: Chemicals interactions in the body may have a synergistic (a), additive (b), and antagonistic (c) effect. For each, chemicals A and B are on one side of a "seesaw", and their combined effect (A+B) is on the other side. In the synergistic effect, the combined effect exceeds the sum of the effects of individual treatments. The opposite is true for the antagonistic effect. In the additive effect, the combined effect equals the sum of effects by individual treatments. Image by Tae Jin Cho et al., MDPI, Basel, Switzerland (CC-BY).

In contrast, if taking both drugs A and B simultaneously increased heart rate by less than 10 beats per minute (less than their sum), their interaction would be considered an **antagonistic effect**, indicating that they interfere with each other. For example, ethanol (found in alcoholic beverages) and methanol (wood alcohol) both have toxic effects, but methanol is more immediately damaging. When methanol is ingested, they body converts it to dangerous compounds that cannot be easily removed from the body. Ethanol can used to treat methanol poisoning because it blocks the enzymes that facilitate these reactions, providing the body an opportunity to eliminate the methanol.

If combining drugs A and B increased heart rate more than 10 beats per minute, their interaction would be a **synergistic effect**; that is, their combined effect was greater than the sum of their individual effects. For example, smoking combined with asbestos exposure have a synergistic effect in causing lung cancer.

The Dose-Response Curve

For centuries, scientists have known that just about any substance is toxic in sufficient quantities. It is a thus common saying among toxicologists that "the dose makes the poison". In fact, too high a dosage (amount) of an otherwise helpful drug can cause negative health effects or even death. Similarly, 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 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, testing on animals, and experiments on cell cultures. A dose that is lethal to 50% of a population of test animals is called the **lethal dose-50%**, or **LD_{50}** (Table $15.4.b$). Determination of the LD_{50} is required for new synthetic chemicals in order to give a measure of their toxicity. Because a single conventional LD_{50} test may kill as many as 100 animals, the United States and other members of the Organization for Economic Cooperation and Development agreed in December 2000 to phase out the LD_{50} test in favor of alternatives that greatly reduce (or even eliminate) deaths of the test animals.

Table $15.4.b$***:*** *The LD_{50} values for some insecticides. In each case, the chemical was fed to laboratory rats. Note that the lower the LD_{50}, the more toxic the chemical.*

Chemical	Category	Oral LD_{50} in Rats (mg/kg)
Aldicarb ("Temik")	Carbamate	1
Carbaryl ("Sevin")	Carbamate	307
DDT	Chlorinated hydrocarbon	87
Dieldrin	Chlorinated hydrocarbon	40
Diflubenzuron ("Dimilin")	Chitin inhibitor	10,000
Malathion	Organophosphate	885
Methoprene	JH mimic	34,600
Methoxychlor	Chlorinated hydrocarbon	5,000
Parathion	Organophosphate	3
Piperonyl butoxide	Synergist	7,500
Pyrethrins	Plant extract	200
Rotenone	Plant extract	60

A dose that causes 50% of a population to exhibit any significant response, whether therapeutic or harmful (hair loss, stunted development, etc.), is referred to as the **effective dose-50%**, or **ED_{50}** (figure $15.4.h$). Some toxins have a threshold dose below which there is no apparent effect on the exposed population, called the **no-observed-adverse-effect level** (**NOAEL;** figure $15.4.i$). The lowest dose at which any negative effect is apparent is called the **lowest-observed-adverse-effect level** (**LOAEL**). Between NOAEL and LOAEL, there may be a noticeable but harmless effect.

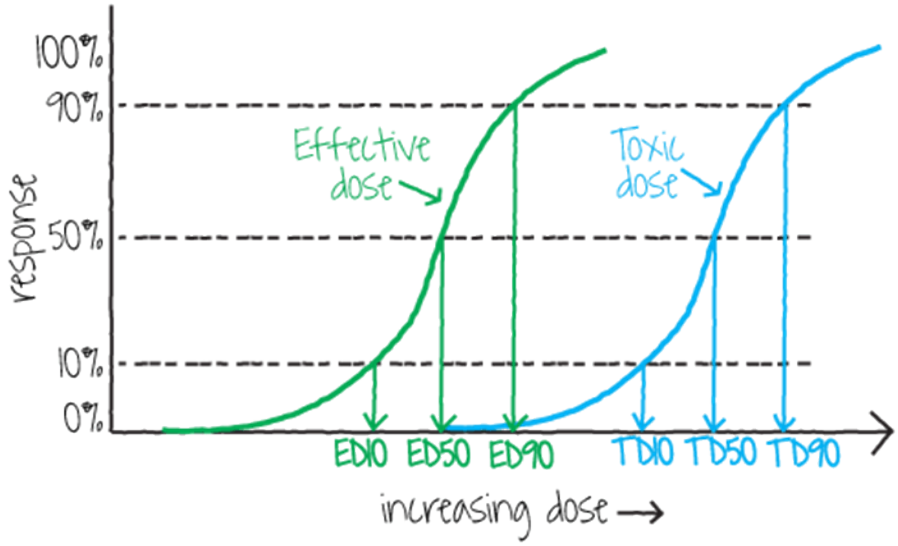

Figure 15.4.h: A dose-response curve shows the percentage of individuals demonstrating a response to a drug based on dosage. The **effective dose-50%** (ED_{50}) is the dosage at which half of the population demonstrates an effect. The toxic dose-50% (TD_{50}) is the dosage at which half of the population is poisoned by the drug. The **lethal dose-50%** (LD_{50}), the dosage at which half of the population dies, could be illustrated by a third curve to the right. Image by U.S. National Library of Medicine (public domain).

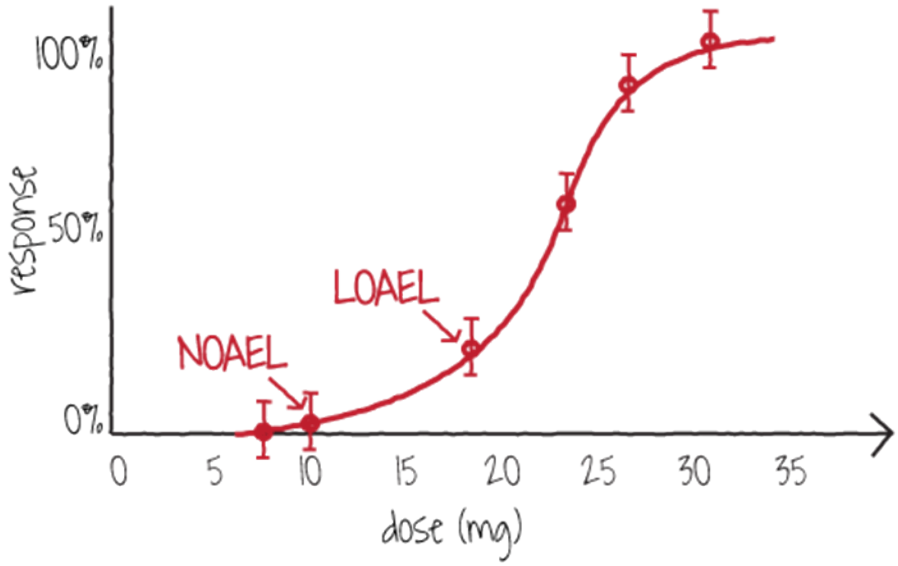

Figure 15.4.i: A dose-response curve illustrating the **no-observed-adverse-effect level** (**NOAEL**) and **lowest-observed-adverse-effect level** (**LOAEL**). Image by U.S. National Library of Medicine (public domain).

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 highly hazardous pesticides (classified by the World Health Organization as class Ib) using hand pump backpack sprayers (figure 15.4.g). The LD_{50} for class Ib pesticides is 5-50 or 20-200 mg/kg for oral ingestion in solid or liquid form, respectively. For dermal (skin) exposure, the LD_{50} is 10-100 or 40-400 mg/kg for solids and liquids, respectively. The LD_{50} class III pesticides, which are considered only slightly hazardous, is at least 10 times greater that that for class Ib pesticides.

Figure 15.4.g: This Vietnam farmer sprays pesticides using a backpack sprayer with little personal protection, similar to what is used by Ecuador potato farmers. Image by Roy Bateman at English Wikipedia (CC-BY-SA).

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.

Precautionary Principle

Determining a safe dosage from a dose-response curve employs the **precautionary principle**, which put simply, embodies the phrase "It's better safe than sorry." Actions that follow the precautionary principle allow margin to ensure safety in the case that a toxin or drug is later found to have negative effect at a lower dosage than first detected. The safe dosage is often set to 1% or even 0.1% of the NOAEL.

The precautionary principle is sometimes applied to other components of environmental toxicology. For example in the European Union (EU), manufacturers must demonstrate the safety of their product before it is sold. While this is also required in the U.S. for chemicals that have not been used before, there is no such rule for existing products. It is instead the responsibility of Environmental Protection Agency to demonstrate that products already on the market are unsafe before banning them. In summary, the precautionary principle is applied to regulating potential toxins in products in both the EU and U.S.; however, the EU's applies the precautionary principle more broadly. The EU errors on the side of caution, potentially banning chemicals that are harmless until they are proven safe, but the U.S. risks exposure to potential toxins before their safety is determined.

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  - Environmental Toxicology
  - The Impacts of Environmental Conditions
  - Environmental Health
  - Energy Flow through Ecosystems
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15.5: Environmental Hazard Reduction

Public Health Organizations

A large number of international programs and agencies are involved in efforts to promote global public health. Among their goals are developing infrastructure in health care, public sanitation, and public health capacity; monitoring infectious disease occurrences around the world; coordinating communications between national public health agencies in various countries; and coordinating international responses to major health crises. In large part, these international efforts are necessary because disease-causing microorganisms know no national boundaries.

International public health issues are coordinated by the **World Health Organization** (WHO), an agency of the United Nations. Of its roughly $4 billion budget for 2015–16, about $1 billion was funded by member states and the remaining $3 billion by voluntary contributions. In addition to monitoring and reporting on infectious disease, WHO also develops and implements strategies for their control and prevention. WHO has had a number of successful international public health campaigns. For example, its vaccination program against smallpox, begun in the mid-1960s, resulted in the global eradication of the disease by 1980. WHO continues to be involved in infectious disease control, primarily in the developing world, with programs targeting malaria, HIV/AIDS, and tuberculosis, among others. It also runs programs to reduce illness and mortality that occur as a result of violence, accidents, lifestyle-associated illnesses such as diabetes, and poor health-care infrastructure.

WHO maintains a global alert and response system that coordinates information from member nations. In the event of a public health emergency or epidemic, it provides logistical support and coordinates international response to the emergency. The United States contributes to this effort through the **Centers for Disease Control and Prevention** (CDC), an agency of the Department of Health and Human Services (figure $15.5.a$). The CDC carries out international monitoring and public health efforts, mainly in the service of protecting US public health in an increasingly connected world. Similarly, the European Union maintains a Health Security Committee that monitors disease outbreaks within its member countries and internationally, coordinating with WHO.

Figure $15.5.a$: The Centers for Disease Control and Prevention is charged with protecting the public from disease and injury. Image by CDC (public domain).

One way that the CDC carries out this mission is by overseeing the National Notifiable Disease Surveillance System (NNDSS) in cooperation with regional, state, and territorial public health departments. The NNDSS monitors diseases considered to be of public health importance on a national scale. Such diseases are called notifiable diseases or reportable diseases because all cases must be reported to the CDC. A physician treating a patient with a notifiable disease is legally required to submit a report on the case. Notifiable diseases include HIV infection, measles, West Nile virus infections, and many others. Some states have their own lists of notifiable diseases that include diseases beyond those on the CDC's list.

Notifiable diseases are tracked by epidemiological studies and the data is used to inform health-care providers and the public about possible risks. The CDC publishes the *Morbidity and Mortality Weekly Report* (*MMWR*), which provides physicians and health-care workers with updates on public health issues and the latest data pertaining to notifiable diseases. Table $15.5.a$ is an example of the kind of data contained in the *MMWR*.

Table $15.5.a$***:*** *Incidence of Four Notifiable Diseases in the United States, Week Ending January 2, 2016*

Disease	Current Week (Jan 2, 2016)	Median of Previous 52 Weeks	Maximum of Previous 52 Weeks	Cumulative Cases 2015
Campylobacteriosis	406	869	1,385	46,618
Chlamydia trachomatis infection	11,024	28,562	31,089	1,425,303
Giardiasis	115	230	335	11,870
Gonorrhea	3,207	7,155	8,283	369,926

The current *Morbidity and Mortality Weekly Report* is available online.

Strategies for Reducing Environmental Hazards

Providing access to clean water is an important strategy for reducing environmental hazards. Because lack of clean water is responsible for diarrheal and other infectious diseases, particular in developing countries, access to clean water limits disease spread (a biological hazard). Furthermore, clean water reduces exposure to toxins (chemical hazards). This can be achieved through digging wells and establishing water treatment facilities. Improving sanitation and hygiene (for example, by supplying latrines, [figure $15.5.b$] and handwashing stations) further reduces the spread of infectious disease.

Figure $15.5.b$: When adequate plumbing is not available, latrines, such as this pit latrine, prevent sewage from polluting water supplies. Image by SuSanA Secretariat (CC-BY).

In Sub-Saharan Africa and South Asia, the use of pipe filters helped eradicate Guinea worm disease, which is caused by a parasitic worm. People are infected by this disease when they drink water contaminated by small animals called copepods that house the larvae. Once in the body, the larvae mature in the abdomen, and adult worms eventually (and painfully) exit through the skin. If an infected person enters a body of water at this stage, adult worms release more larvae into the water, continuing their life cycle. Pipe filters are straw-like structures that contain openings small enough to allow the passage of water but not copepods, preventing infection.

Another strategy to limit exposure to biological hazards is to reduce exposure to disease vectors. Depending on the specific vector and disease this could involve removing standing water (which facilitates mosquito reproduction), application of pesticides, or use of netting (figure $15.5.c$). Biological control is also slowly emerging in vector control in public health and in areas that for

a long time mainly focused on chemical vector control of the *Anopheles* mosquito (the vector of malaria) and the black fly (the vector of river blindness, caused by a parasitic worm). The release of sterile males has been used to control the tsetse fly, the vector of African sleeping sickness. Vaccinating animals that harbor diseases (reservoirs) can also limit the chance of infection.

Figure $15.5.c$: A net excludes mosquitos, which are disease vectors. The *Anopheles* mosquito is only active at night, and thus sleeping inside of a net can limit exposure to malaria. Image by Presidents Mosquito Initiative a component of the U.S. Government's Global Health Initiative (public domain).

Because air pollution exposes individuals to toxins, limiting air pollution is another means of reducing environmental hazards. This can involve energy conservation, using clean energy, such as solar or wind (rather than burning fossil fuels), enforcing air pollution standards on industry, and implementing pollution-reducing technologies, at an industry or household scale. A main source of indoor air pollution is cooking using a fire indoors. Solar ovens provide a pollution-free alternative for people who do not have access to electricity or gas for cooking (figure $15.5.d$).

Figure $15.5.d$: Solar ovens are a pollution-free option for cooking food if electricity or gas is not available. Image by SUN OVEN (public domian).

The public have an important role in environmental hazard reduction. Firstly, the public must engage in behaviors to prevent disease spread and minimize contact with toxins, and public health education is critical to this. In the case of Guinea worm disease, individuals learned how to use pipe filters and shy they must avoid submerging wounds from the worms in bodies of water to limit disease spread. In the case of COVID-19, individuals are learning to reduce disease transmission by

employing frequent handwashing, mask wearing, and social distancing (figure $15.5.e$).

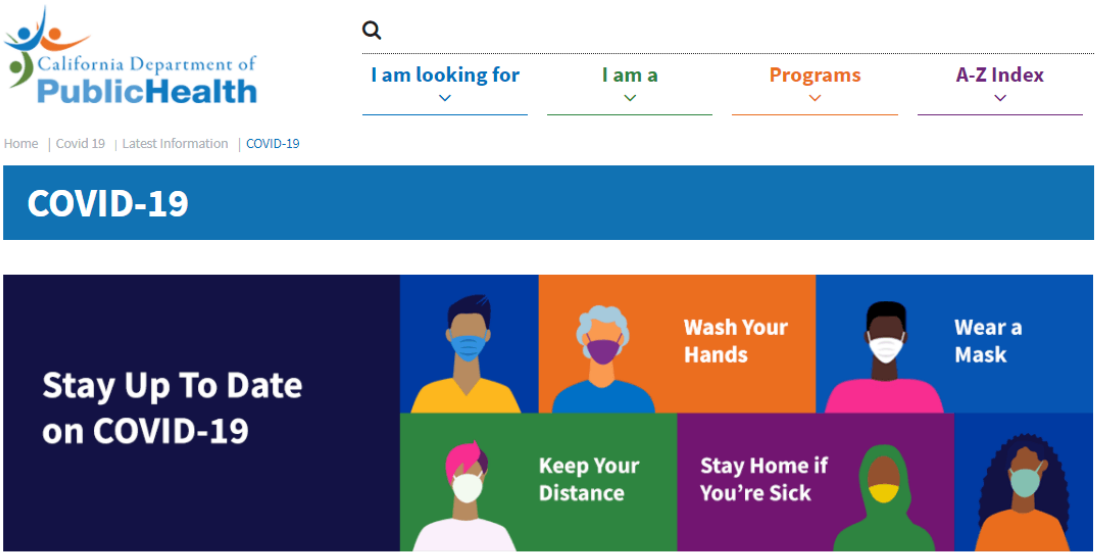

Figure $15.5.e$: The California Department of Public Health website includes guidelines for limiting disease spread. The text reads "Stay Up To Date on COVID-19. Wash Your Hands. Wear a Mask. Keep Your Distance. Stay Home if You're Sick." Image from the CDPH website (public domain).

The public can also support policies that reduce exposure to environmental hazards. For example, many states have laws that reduce exposure to secondhand smoke. The Toxic Substances Control Act (TSCA) bans or regulates harmful chemicals, such as asbestos and heavy metals (figure $15.5.f$)..

Figure $15.5.f$: Asbestos removal from a building in the United Kingdom (UK). While asbestos is fully banned in the UK, only certain uses of asbestos are banned in the United States under the Toxic Substances Control Act . Image by Fevs101 (CC-BY-SA).

Many strategies for reducing environmental health hazards directly align with the United Nations Sustainable Development Goals, particularly goals 3 (Good Health and Well-Being) and 6 (Clean Water and Sanitation).

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15.6: Data Dive- Cholera Cases Worldwide

Overview

The World Health Organization (WHO) seeks to promote health and safety for humanity, especially the most vulnerable. What this means is they do everything from basic primary care, to research, to data inventory, to health education, and to many other imperative health initiatives worldwide. When it comes to data, they keep up to date records for chronic and acute diseases, especially those that can cause global/local health emergencies. Generally, the WHO tracks the number of cases (infection rates) and case fatalities for each disease. However, there are many other statistics they can analyze depending on the level of accuracy and detail of the data they receive. They can also break up or group their statistics by country or by continent (as you see below). In addition, the WHO can be a great database for researchers around the globe. Below is a graph created by WHO data on cholera from a 2019 publication about cholera epidemiology:

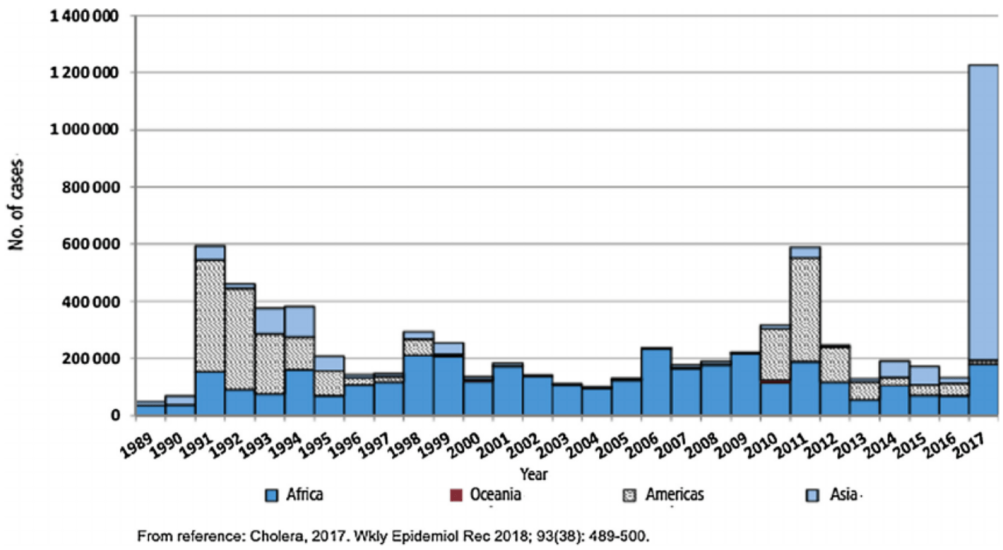

Figure $15.6.a$: Number of cholera cases by world region for 20+ year period. Graph by Deen J, Mengel MA, Clemens JD 2019 (CC-BY4.0)

Questions

1. What kind of graph is this?
2. What is the independent (explanatory) variable and the dependent (response) variable?
3. Which continent has the most consistent cholera cases?
4. Describe the patterns you see in cholera cases for the Americas and Asia from 1989 to 2017.
5. In what ways do you think the WHO uses data observed in the graph above to make choices into the future? Provide at least two ideas/examples.

Raw Data For Above Graph(s)

Raw data table link for above graph. (CC-BY4.0)

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15.7: Review

Summary

After completing this chapter you should be able to...

- Compare traditional and modern environmental hazards.
- Provide examples of biological, chemical, and physical hazards.
- Distinguish between morbidity and mortality.
- Distinguish between disease prevalence and incidence.
- Compare sporadic, endemic, epidemic, and pandemic patterns of incidence.
- Compare contact, vector, and vehicle modes of transmission and provide examples of how environmental degradation has increased transmission.
- Identify examples of emerging and reemerging infectious diseases.
- Briefly explain how vaccines work and their role in eradicating infectious diseases.
- Describe how antibiotic resistance evolves.
- Identify the three main routes of exposure to chemicals.
- Identify and define five factors that impact a chemical's safety.
- Compare additive, antagonistic, and synergistic toxicological interactions.
- Explain how the lethal dose-50% is determined from a dose-response curve.
- Provide examples of strategies for reducing environmental hazards.

Environmental health focuses on how the natural and human-built surroundings as well as behaviors affect human well-being. **Traditional hazards** are related to poverty and mostly affect low-income people and those in developing countries whereas **modern hazards** result from technological development and prevail in industrialized countries. Environmental health hazards are classified as biological (infectious diseases), chemical (exposure to toxins), or physical.

Epidemiology is the science underlying public health. **Morbidity** means being in a state of illness, whereas **mortality** refers to death; both **morbidity rates** and **mortality rates** are of interest to epidemiologists. **Incidence** is the number of new cases (morbidity or mortality), usually expressed as a proportion, during a specified time period; **prevalence** is the total number affected in the population, again usually expressed as a proportion. **Sporadic diseases** only occur rarely and largely without a geographic focus. **Endemic diseases** occur at a constant (and often low) level within a population. **Epidemic diseases** and **pandemic diseases** occur when an outbreak occurs on a significantly larger than expected level, either locally or globally, respectively. Diseases may be spread through **contact transmission** (direct physical interaction or indirect interaction through shared objects), **vehicle transmission** (through water, food, or air), or **vector transmission** (by an animal). Ecosystem degradation can exacerbate disease spread through creating conditions where vectors, pathogens, or reserviors thrive.

Emerging and reemerging diseases have been defined as infectious diseases of humans whose occurrence during the past two decades has substantially increased or threatens to increase in the near future relative to populations affected, geographic distribution, or magnitude of impacts. **Vaccination** has been used to successfully eradicate several infectious diseases by stimulating a specific immune response. For remaining diseases that are commonly treated with medications, **antibiotic resistance** continues to be a global problem. New forms of antibiotic resistance can cross international boundaries and spread between continents.

Environmental toxicology is the scientific study of the health effects associated with exposure to toxins. The three mains routes of exposure to toxins are inhalation, ingestion, and skin or eye contact. Potency, persistence, solubility, bioaccumulation, and biomagnification all affect a chemical's safety. **Bioaccumulation** refers to the buildup of a toxin over an individual's lifetime whereas **biomagnification** occurs to increasing concentrations of a toxin as it moves up the food chain. Toxins may interact with each other in an additive, antagonistic, or synergistic way. The potency of a toxin is measure by the **lethal dose-50%** (**LD_{50}**), the concentration that is fatal to 50% of the test population. This is determined through a **dose-response curve**, which shows the percent of individuals affected as a function of concentration.

The **World Health Organization (WHO)** is an agency of the United Nations that collects and analyzes data on disease occurrence from member nations. WHO also coordinates public health programs and responses to international health emergencies. In the United States, the **Centers for Disease Control and Prevention** monitors **notifiable diseases** and publishes weekly updates in

the *Morbidity and Mortality Weekly Report*. Strategies for reducing environmental hazards include providing access to clean water, improving sanitation and hygiene, and limiting exposure to disease vectors. The public serves an important role by engaging in behaviors that limit disease spread or exposure to toxins and supporting policies that limit environmental hazards.

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UNIT 5: ENERGY

Energy for lighting, heating and cooling our buildings, manufacturing products, and powering our transportation systems comes from a variety of natural sources. **Nonrenewable energy** is finite and cannot be replenished within a human timescale. Examples include nuclear energy and fossil fuels. In contrast **renewable resources** are replenished on shorter time scales, and it is thus possible to use them indefinitely. All energy sources have and some environmental and health cost, and the distribution of energy is not equally distributed among all nations.

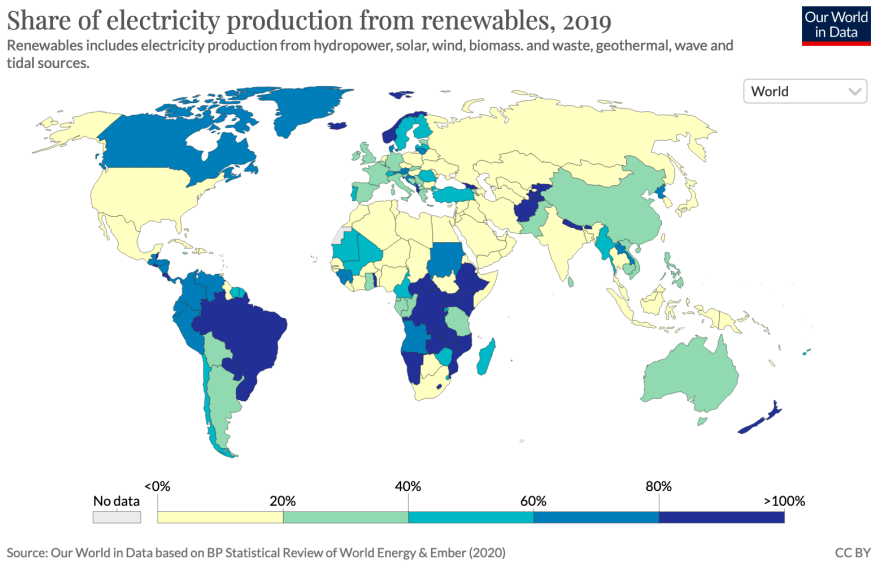

Figure $5.a$: How much of the worlds energy comes from renewable sources. Graph by Our World in Data (CC-BY)

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16: Fossil Fuels

16.1: Types of Fossil Fuels and Formation

16.2: Mining, Processing, and Generating Electricity

16.3: Fossil Fuel Consumption

16.4: Consequences of Fossil Fuels

16.5: Data Dive- Global Fossil Fuel Consumption

16.6: Review

18: Renewable Energy

18.1: Renewable Energy History and Consumption

18.2: Wind Energy

19.3: Solar Energy

18.4: Geothermal Energy

18.5: Hydropower

18.6: Biofuels (Biomass Energy)

18.7: Energy Conservation
18.8: Data Dive- Global Renewable Energy Generation
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Thumbnail image - "Renewable energy on the grid" is in the Public Domain

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16: FOSSIL FUELS

Chapter Hook

Human use of coal dates back thousands of years, and archeologists have found evidence for its use and excavation across the globe. As such, it is impossible to know how coal's utility was discovered. In the Americas, Aztecs used coal for fuels and decoration. In Europe, Romans were noted as early as the late 2nd century AD to be extracting coal and using it to smelt iron ore and heat their famous public baths. Coals earliest reference in writings was by a Greek scientist Theophrastus (c.371-267 BC) about its usage in metalworking. In Asia, the Chinese are known to have been mining and using coal as far back as 3490 BC. Overall, there is a deep history of human usage of coal. As there is a limited supply, it regrettably won't last forever.

Figure $16.a$**:** Fossil charcoal in weathered coal. Image by James St. John in Wikimedia Commons (CC-BY2.0)

16.1: Types of Fossil Fuels and Formation

16.2: Mining, Processing, and Generating Electricity

16.3: Fossil Fuel Consumption

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16.1: Types of Fossil Fuels and Formation

Fossil fuels are nonrenewable sources of energy formed from the organic matter of plants and microorganisms that lived millions of years ago. This energy was originally captured via photosynthesis by living organisms such as plants, algae, and photosynthetic bacteria. Sometimes this is known as fossil solar energy since the energy of the sun in the past has been converted into the chemical energy within a fossil fuel. As discussed in Food Chains and Food Webs and Matter, the organic molecules store chemical energy, which is released when the higher energy (less stable) bonds in these molecules are broken to form lower energy (more stable) bonds. Fossil fuels are nonrenewable because their formation took millions of years. Furthermore, higher productivity in the ancient environment allowed for more fossil fuel accumulation, meaning that the fossil fuel reserves available now could not necessarily be regenerated millions of years in the future.

Fossil fuels are composed primarily of **hydrocarbons** (molecules of just carbon and hydrogen), but they contain lesser amounts nitrogen, sulfur, oxygen, and other elements as well. The precise chemical structures vary depending on the type of fossil fuel (coal, oil, or natural gas). The molecules in coal tend to be larger than those in oil and natural gas. Coal is thus solid at room temperature, oil is liquid, and natural gas is in a gaseous phase. Specifically, **coal** is a black or dark brown solid fossil fuel found as coal seams in rock layers formed from ancient swamp vegetation. Both oil and natural gas are fossil fuels found underground that formed from marine microorganisms. **Oil** (petroleum) is a liquid fossil fuel and consists of a variety of hydrocarbons while **natural gas** is a gaseous fossil fuel that consists of mostly methane and other small hydrocarbons.

Coal

Coal is the product of fossilized swamps, although some older coal deposits that predate terrestrial plants are presumed to come from algal buildups. Coal was formed when plant material is buried, heated, and compressed in oxygen-poor conditions over a long period of time (figure $16.1.a$). Millions of years ago, continents were in different locations with different climates, and swamp-like vegetation covered many regions. When the vegetation died, it could not fully decompose due to oxygen-poor conditions. Instead, it formed peat (a brown substance high in organic content). The peat was buried and formed coal after millions of years of high pressure and temperature. The pressure was from the weight of sediments as well as from continental collisions.

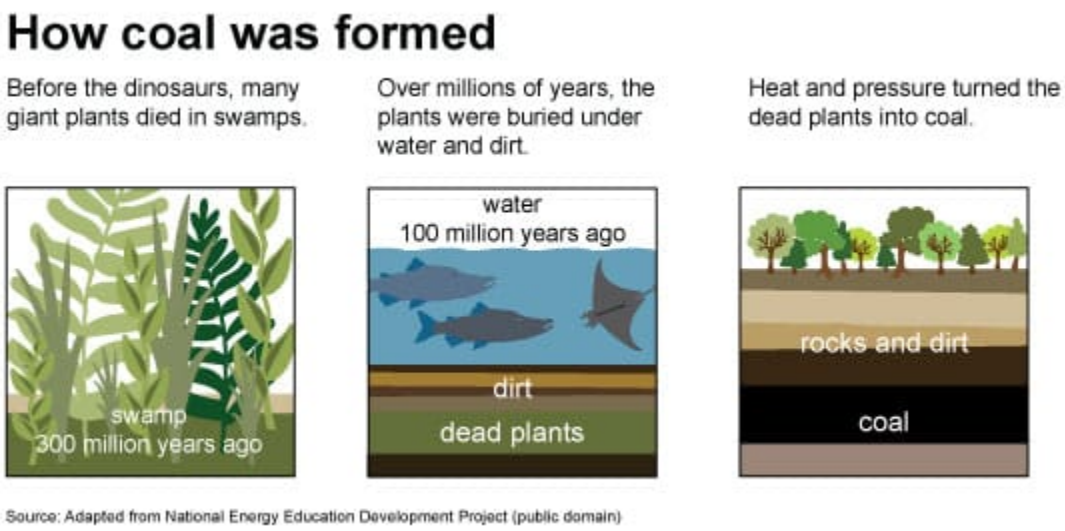

Figure $16.1.a$: Coal was formed when large plants in swamps died 300 million years ago (before the dinosaurs). Over millions of years, this vegetation was buried under water and dirt (100 million years ago). Eventually, heat and pressure turned the dead plants into coal, which is found under layers of rock and dirt. Image from U.S. Energy Information Administration/National Energy Education Development Project (public domain).

There are several different types of coal ranging in quality (figure $16.1.b$). The more heat and pressure that coal undergoes during formation, the greater is its fuel value and the more desirable is the coal. The general sequence of a swamp turning into the various stages of coal are as follows:

Swamp → Peat → Lignite → Subbituminous coal → Bituminous coal → Anthracitic coal → Graphite

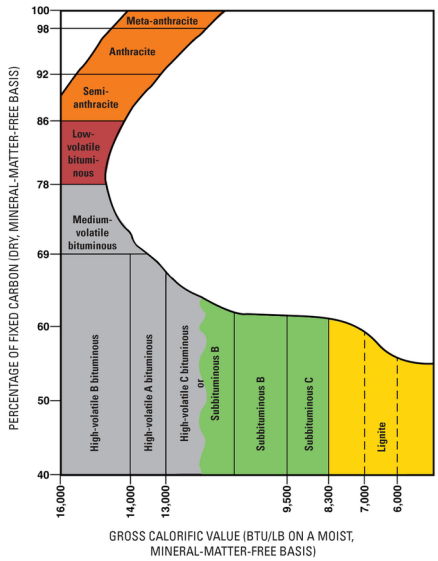

Figure $16.1.b$: Coal rankings depend on energy content, measured as gross calorific value (how much energy is released from combustion) and carbon content that can be burned (percentage of fixed carbon). Anthracitic coal (orange) is the highest quality coal, with high energy and carbon content. Next in quality is bituminous coal (gray), subbituminous coal (green), and lignite (yellow). All three have less carbon content than anthracitic coal. Bituminous coal retains high energy content, but subbituminous coal and lignite have lower energy content. Image by USGS (public domain).

Specifically, peat compacts to form solid rock through a process called **lithification**, producing **lignite** (brown coal, a low-quality form of coal). With increasing heat and pressure, lignite turns to **subbituminous coal** and **bituminous coal**. Lignite, subbituminous coal, and bituminous coal are considered sedimentary rocks because they from from compacted sediments. At very high heat and pressure, bituminous coal is transformed to **anthracite**, a high-grade coal that is the most desirable coal since it provides the highest energy output (figure $16.1.c$). Anthracite is considered a metamorphic rock because it has been compacted and transformed to the extent that it is denser than the other forms of coal and no longer contains sheet-like layers of sediments. With even more heat and pressure driving out all the components that evaporate easily and leaving pure carbon, anthracite can turn to **graphite**.

Figure $16.1.c$: Anthracitic coal, the highest grade of coal.

Oil and Gas

Oil and natural gas formed from ancient marine microorganism (**plankton**). When plankton died, they were buried in sediments. As with coal, oxygen-poor conditions limited decomposition. As sediments continued to accumulate, the dead organisms were further buried. High temperature and pressure over millions of years ultimately produced oil and natural gas from these dead organisms.

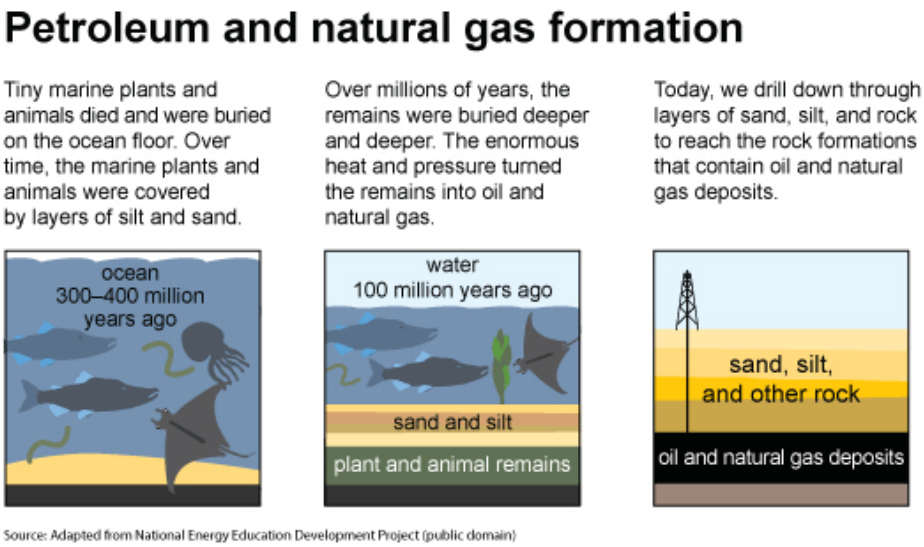

Figure $16.1.d$: Petroleum (oil) and natural gas were formed from marine microorganisms. (The image text mentions tiny marine plants, but they were primarily algae and photosynthetic bacteria rather than plants.) These were covered by layers of silt and sand 300-400 million years ago. Over millions of years, the remains were buried deeper and deeper. They are pictured 100 million years ago. The enormous heat and pressure turned the remains into oil and natural gas. Now, oil and natural gas deposits are found underground and can be extracted via drilling through the layers of sand, silt, and rock. Image from U.S. Energy Information Administration/National Energy Education Development Project (public domain).

As the rock forms from the sediments that originally trapped the plankton, the oil and gas leak out of the **source rock** due to the increased pressure and temperature, and migrate to a different rock unit higher in the rock column. If the rock is porous and permeable rock, then that rock can act as a **reservoir** for the oil and gas. Petroleum is usually found one to two miles (1.6 – 3.2 km) below the Earth's surface, whether that is on land or ocean.

A **trap** is a combination of a subsurface geologic structure and an impervious layer that helps block the movement of oil and gas and concentrates it for later human extraction. Traps pool the fluid fossil fuels into a configuration in which extraction is more likely to be profitable, and such fossil fuels are called **conventional oil and natural gas** (figure $16.1.e$). Extraction of oil or gas outside of a trap (**unconventional oil and natural gas**) is less efficient and more expensive; sometimes it is not economically viable at all (does not produce a profit). Examples of unconventional fossil fuels include oil shale, tight oil and gas, tar sands (oil sands), and coalbed methane.

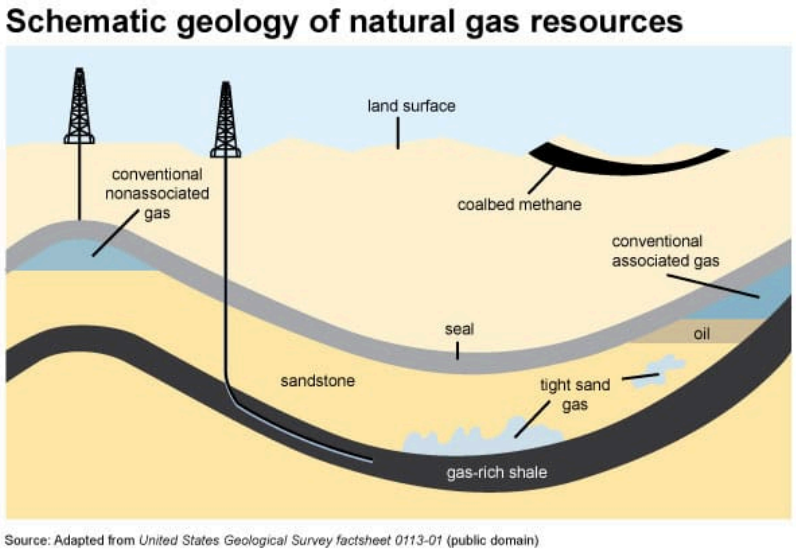

Figure $16.1.e$: Conventional oil and natural gas deposits are trapped beneath impervious rock (gray). Conventional natural gas may be associated with oil or nonassociated. Coalbed methane and tight gas found in shale and sandstone are examples of unconventional fossil fuels. Image from USGS/EIA (public domain)

Oil Shale

Oil shale is a fine-grained sedimentary rock that sometimes contains **kerogen**, a solid material from which petroleum products can ultimately be manufactured. In order extract the fossil fuels, the material has to be mined and heated, which is expensive and typically has a negative impact on the environment.

Tight Oil and Natural Gas

Tight oil and natural gas are also trapped in shale rock, fine-grained sedimentary rocks with relatively high porosity and low permeability. They differ from oil shale in that they can be extracted through a process called hydraulic fracturing (fracking).

Similarly, fracking can be used to extract natural gas from tight sands, which are gas-bearing, fine-grained sandstones or carbonates (rocks made of minerals containing carbonate, CO_3^{2-}) with a low permeability.

Tar Sands

Tar sands, or oil sands, are sandstones that contain petroleum products that are highly viscous (like tar), and thus, can not be drilled and pumped out of the ground, unlike conventional oil (figure $16.1.f$). The fossil fuel in question is bitumen, which can be pumped as a fluid only at very low rates of recovery and only when heated or mixed with solvents. Thus, injections of steam and solvent or mining of the tar sands for later processing can be used to extract the tar from the sands. (See related information about strip mining with respect to coal in Mining, Processing, and Generating Electricity.) Alberta, Canada is known to have the largest reserves of tar sands in the world.

Figure $16.1.f$: Tar sandstone from the Miocene Monterrey Formation of California.

Coalbed Methane

Some natural gas is also found associated with coal deposits (**coalbed methane**), consisting of methane produced during coal formation.

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- Shale Gas 101. Office of Fossil Energy. U.S. Department of Energy. Accessed 01-12-2021. (public domain)
- The Process of Unconventional Natural Gas Production. 2021. United States Environmental Protection Agency. Accessed 01-12-2021. (public domain)

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16.2: Mining, Processing, and Generating Electricity

Fossil fuels must be extracted or mined before use, and the specific method depends on the type of fossil fuel. Coal and natural gas and primarily used for electricity generation, while petroleum is refined to produce fuel for vehicles, planes, and heating as well as other products.

Coal

Mining

Coal is extracted by two principal methods, of which there are many variants: surface mining or subsurface mining. **Surface mining** uses large machines to remove the soil and layers of rock known as **overburden** to expose coal seams that are close to the Earth's surface (figure $16.2.a$). **Strip mining** is a type of surface mining in which overburden is sequentially removed from each stretch (strip) of land. Once overburden is removed from the first strip, coal is removed. Overburden from the second strip is then deposited into the first strip, and coal is removed from the second strip. Overburden from the third strip is then placed in the first strip, and so on. **Mountaintop removal** is a more destructive type of surface mining in which all of the overburden is removed with explosives, revealing the entire coal seam at once (figure $16.2.b$). The large mass of overburden (the mountaintop) is dumped into a nearby valley, and the coal is them removed.

Figure $16.2.a$: Surface mining of coal in Wyoming. Image by Bureau of Land Management (public domain).

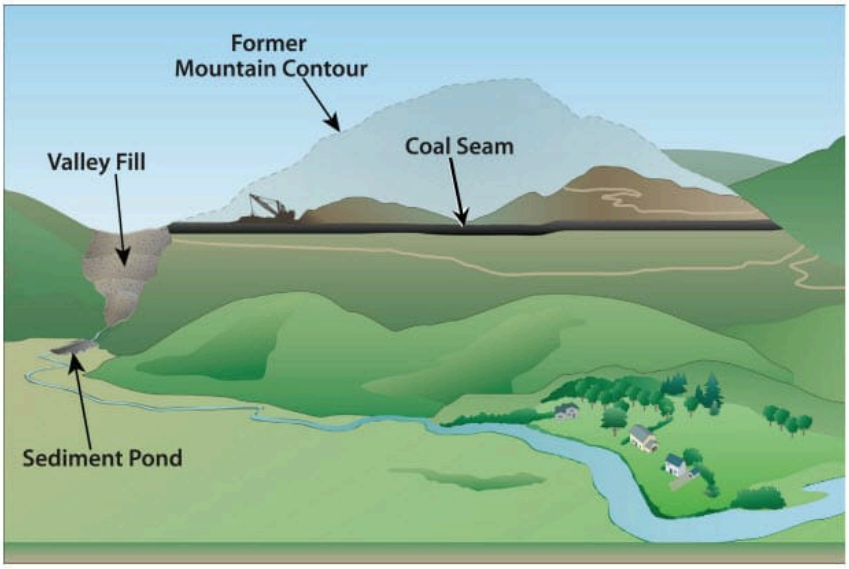

Figure $16.2.b$: Left: Mountaintop removal uses explosives to loosen overburden at the top of a mountain, which is then displaced into a nearby valley (valley fill). The underlying coal seam is then extracted. A sediment pond collects soil that erodes from the valley fill. Image by EPA (public domain). Right: A mountaintop removal site. Image by JW Randolph (public domain)

Subsurface mining (deep mining) employs underground tunnels to access deeper deposits (figure $16.2.c$). Some underground mines are thousands of feet deep, and extend for miles. Miners ride elevators down deep mine shafts and travel on small trains in long tunnels to get to the coal. The miners use large machines that dig out the coal. In **drift mines**, a tunnel is dug horizontally into the side of a mountain. In **slope mines**, this tunnel is diagonal. In **shaft mines**, elevators are used to move coal through vertical tunnels.

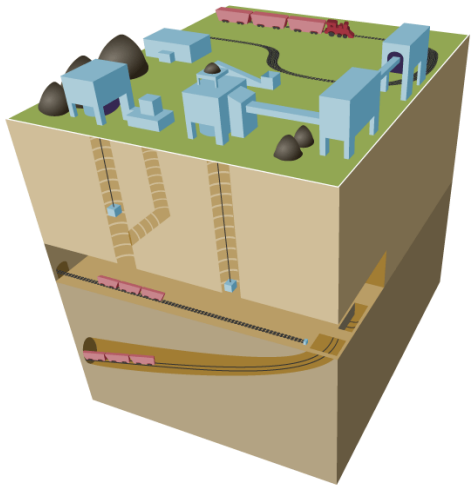

Figure 16.2.c: Subsurface mining involves digging tunnels to access coal deposits that are deep underground. Image by National Energy Education Development Project/EIA (public domain)

Processing of Coal

Once mined, coal may go to a preparation plant located near the mining site where it is cleaned and processed to remove impurities such as rocks and dirt, ash, sulfur, and other unwanted materials. This process increases the amount of energy that can be obtained from a unit of coal, known as its heating value.

Transport of Coal

Finally, the mined and processed coal must be transported. Transportation can be more expensive than mining the coal. Nearly 70% of coal delivered in the United States is transported, for at least part of its trip, by train (figure 16.2.e). Coal can also be transported by barge, ship, or truck. Coal can also be crushed, mixed with water, and sent through a slurry pipeline. Sometimes, coal-fired electric power plants are built near coal mines to lower transportation costs.

Figure 16.2.e: A freight train loaded with coal briquettes, formed from compressed coal dust, in Morwell, Victoria, Australia. Image and caption (modified) by CSIRO (CC-BY).

Generating Electricity from Coal

Once at the power plant, coal is first pulverized into a fine powder and then mixed with hot air and blown into a furnace (figure $16.2.f$). This allows for the most complete combustion (burning) and maximum heat release. Purified water, pumped through pipes inside a boiler, is turned into steam by the heat from the combustion of coal. The high pressure of the steam pushing against a series of giant turbine blades turns the turbine shaft. The turbine shaft is connected to the shaft of the generator, where magnets spin within wire coils to produce electricity. After doing its work in the turbine, the steam is drawn into a condenser, a large chamber in the basement of the power plant. In this important step, millions of gallons of cool water from a nearby source (such as a river or lake) are pumped through a network of tubes running through the condenser. The cool water in the tubes converts the steam back into water that can be used over and over again in the plant. The cooling water is returned to its source without any contamination except at a higher temperature than when first extracted from the river or lake.

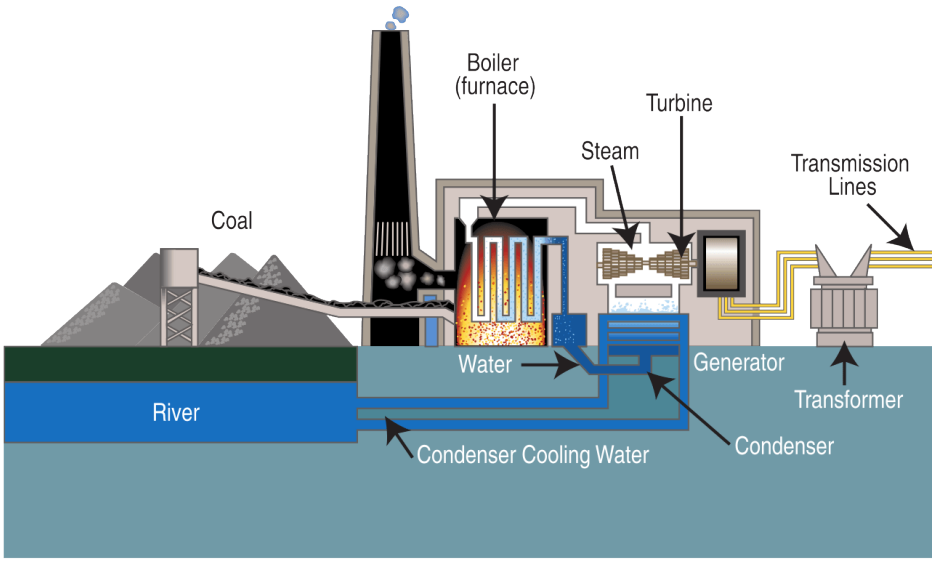

Figure $16.2.f$: Left: Coal power plant in Helper, Utah. Right: Diagram of a typical steam-cycle coal power plant (proceeding from left to right). Coal enters the boiler (furnace), where it is burned. This boils water, producing steam. The steam turns a turbine, powering a generator. The resultant electricity is passed through a transformer (which changes the voltage) and is then sent through transmission lines. The steam cools and condenses back to liquid water in the condenser. This is facilitator by cooling water from a nearby river. Right image by Tennessee Valley Authority (public domain).

This video shows how heat energy can be used to generate electricity.

YouTube Video

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Oil and Natural Gas

Extraction of Conventional Oil and Natural Gas

Conventional oil and natural gas are contained under a trap (cap rock). Because natural gas consists of lighter molecules that are in a gaseous form at moderate temperatures, it is found on top of the oil, which may be floating on groundwater. To access conventional oil and natural gas, the trap is first pierced. Initially, they are under high enough pressure, and this drives them out of the well (**primary recovery**). Next, water (or gas) is injected to force more fossil fuels out (**secondary recovery**). Finally, enhanced oil recovery (**tertiary recovery**) may be used to extract further oil by applying heat (injecting steam) or injecting carbon dioxide, other gases, or larger molecules. For example, carbon dioxide causes the oil to thin and expand, making it easier to remove from the rocks. Note that secondary recovery simply increases pressure inside the reservoir whereas tertiary recovery changes the properties of the oil, making it easier to extract (figure $16.2.g$). Each stage of recovery is increasingly expensive, and extraction from a well continues as long as it remains profitable.

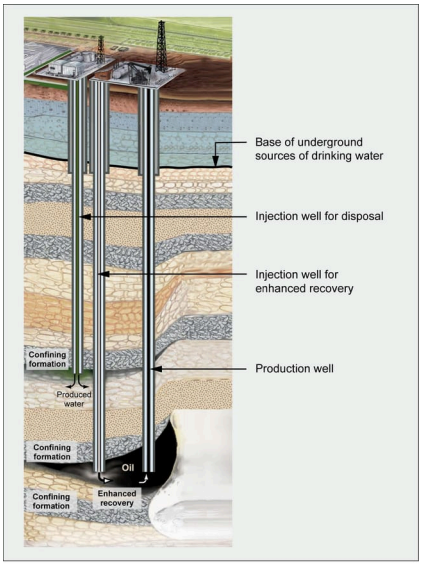

Figure $16.2.g$: Injection wells transfer water, carbon dioxide, or other substances to an oil deposit increase pressure or change the oil's properties, facilitating extraction. On the right is the production well, through which extracted oil flows. This is facilitated by an injection well for enhanced recovery. On the left is an injection well for disposal through with waste water (produced water) is stored underground. Several confining formations trap substances underground. Closer to the top is the base of underground sources of drinking water, meaning that all drinking water is extracted from above this point. Image by Government Accountability Office (public domain).

Oil is mainly obtained by drilling either on land (onshore) or in the ocean (offshore). Early offshore drilling was generally limited to areas where the water was less than 300 feet deep. Oil and natural gas drilling rigs now operate in water as deep as two miles. Floating platforms are used for drilling in deeper waters (figure $16.2.h$). These self-propelled vessels are attached to the ocean floor using large cables and anchors. Wells are drilled from these platforms which are also used to lower production equipment to the ocean floor. Some drilling platforms stand on stilt-like legs that are embedded in the ocean floor. These platforms hold all required drilling equipment as well as housing and storage areas for the work crews. Offshore production is much more expensive than land-based production.

Figure $16.2.h$: A platform for offshore oil drilling. Image by Pixabay/keridjackson (Pixabay license).

Extraction of Unconventional Oil and Natural Gas

Tight oil and natural gas trapped in shale as well as natural gas in tight sands are extracted via **hydraulic fracturing**, informally referred to as “fracking”. This process uses explosives to create new fractures in these low-permeability rocks as well as increase the size, extent, and connectivity of existing fractures and then applies high-pressure fluid. First, a drill permeates the rock layers and then proceeds horizontally. Explosives then fracture rocks, freeing oil and natural gas. Finally, water, sand, and chemicals and injected, which flush out oil and natural gas (figure $16.2.i$).

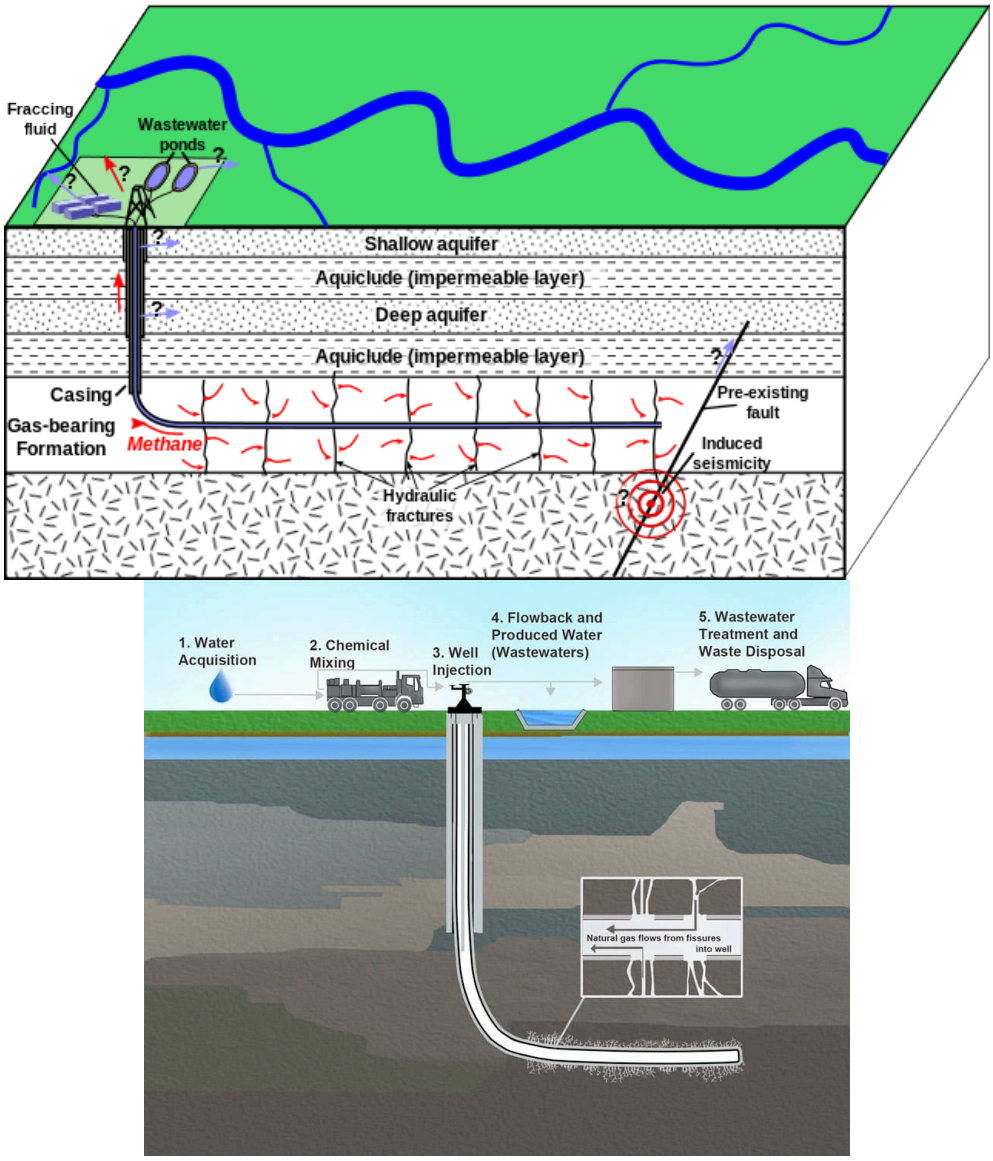

Figure $16.2.i$: Two diagrams of fracking. Water is mixed with sand and chemicals and then injected into shale trapping tight oil and natural gas or tight sand. This flushes fossil fuels from the fissures that were previously created by explosives. Top: This section shows four underground layers. From top to bottom, they are the shallow aquifer, aquiclude (impermeable layer), deep aquifer, and another aquiclude. Fracking fluid is injected underground through a well surrounded by casing into the gas-bearing formation. Methane (red arrows) might escape from hydraulic fractures in this formation. Additionally, when the fractures intersect with a pre-existing fault, induced seismicity (earthquakes) is possible. Aboveground, fracking fluid is stored in wastewater ponds. Blue arrows and question marks indicate places where toxic wastewater may escape and contaminate groundwater such as from storage containers, wastewater ponds, casing, or faults. Bottom: Proper treatment and disposal of the wastewater is needed to limit environmental impact. 1: Water is acquired. 2: Chemicals are mixed. 3: Fracking fluid is injected into the well. Here, natural gas flows from fissures into the well. 4: Fracking results in flowback and produced water (wastewater). 5: Wastewater undergoes treatment and disposal. Bottom image by USGS (public domain).

As mentioned previously, bitumen in tar sands can be extracted by injecting steam, or they may be mined for later processing. Tar sands can mined through strip mining or **open-pit mining**, a type of surface mining that involves forming a progressively deeper hole. The walls of the pit are as steep as can safely be managed. A steep wall means there is less waste overburden to remove and is an engineering balance between efficient mining and mass wasting. Oil shale is extracted by strip mining, creating subsurface mines, or open-pit mining. Oil shale can be burned directly like coal or baked in the presence of hydrogen to extract liquid petroleum (figure $16.2.j$).

Figure $16.2.j$: Underground mining of oil shale in Estonia.

Refining Crude Oil

The result of oil recovery is crude oil (petroleum), which contains many types of hydrocarbons as well as some unwanted substances such as sulfur, nitrogen, oxygen, dissolved metals, and water all mixed together. Unprocessed crude oil is therefore, not generally useful in industrial applications and must first be separated into different useable products (**petrochemicals**) at a refinery. Gasoline (petrol), diesel, tar, and asphalt are examples of petrochemicals.

Fractional distillation is the key process used in oil refineries to separate the components of crude oil. During fractional distillation, crude oil is heated and then allowed to cool. The heaviest compounds sink to the bottom as residues. Components of vaporized crude oil condense at different levels in the distillation column depending on their boiling points, which is primarily due to their molecular sizes. The heaviest compounds (condense near the bottom of the column, where the temperature is still high. Lighter compounds condense at cooler temperatures higher up in the column. Some compounds remain as gases at the top of the column (figure $16.2.k$).

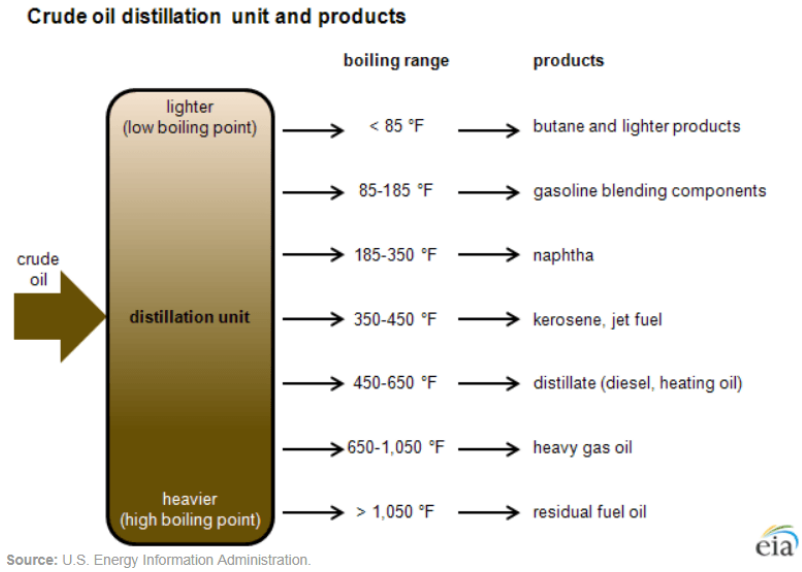

Figure $16.2.k$: The process of fractional distillation involves heating crude oil and allowing the components to cool. As they move up the distillation column, they condense at different levels based on their boiling points. The heaviest compounds have the highest boiling points and condense at the bottom of the column while lighter compounds (low boiling point) condense at the top. From lowest to highest boiling point the petrochemicals produced are residual fuel oil (1050 °F), heavy gas oil (650-1050 °F), diesel and heating oil (450-650 °F), kerosene and jet fuel (350-450 °F), naphtha (used to make gasoline, solvents, cleaning solutions, etc.; 185-350 °F), gasoline blending components (85-185 °F), and butane and lighter products (< 85 °F). Image by U.S. Energy Information Administration (public domain).

The video below explains the process of fractional distillation. The labeled distillation column at 3:00 shows heated crude oil (400 °C) separating into various petrochemicals. From bottom to top, they are bitumen (> 350 °C), diesel (250-350 °C), kerosene (160-250 °C), naphtha (70-160 °C), petrol (20-70 °C), and gas (< 20 °C).

YouTube Video

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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 $16.2.l$). This increase in volume is similar to what happens to popcorn when it is popped. Gasoline makes up the largest fraction of all petroleum products obtained. Other products include diesel fuel and heating oil, jet fuel, petrochemical feedstocks (to manufacture plastics, synthetic rubber, or other chemicals), waxes, lubricating oils, and asphalt.

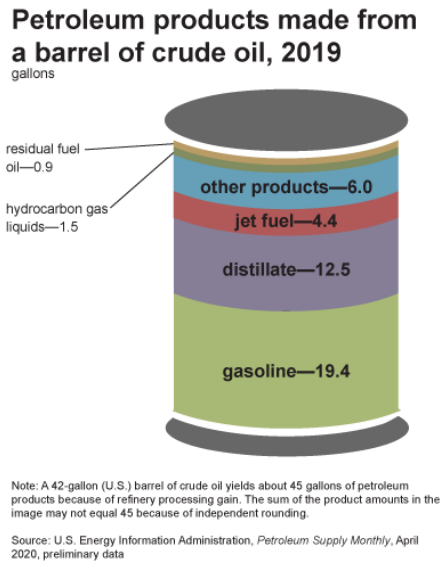

Figure $16.2.l$: Main products (measured in gallons) made from a barrel of crude oil in 2019. These include residual fuel oil (0.9 gallons), hydrocarbon gas (1.5), other products (6.0), jet fuel (4.4), distillate (12.5), and gasoline (19.4). Note: A 42-gallon (U.S.) barrel of crude oil yields about 45 gallons of petroleum products because of refinery processing gain. The sum of the product amounts in the image may not equal 45 because of independent rounding. Image by EIA (public domain).

Transporting Oil and Natural Gas

After the refinery, the gasoline and other fuels created are ready to be distributed for use. A system of pipelines runs throughout the United States to transport oil and fuels from one location to another. There are pipelines that transport crude oil from the oil well to the refinery. At the refinery, there are additional pipelines that transport the finished product to various storage terminals where it can then be loaded onto trucks for delivery, such as to a gas station.

Once natural gas is produced from underground rock formations, it is sent by pipelines to storage facilities and then on to the end user. The United States has a vast pipeline network that transports gas to and from nearly any location in the lower 48 states. There are more than 210 natural gas pipeline systems, using more than 300,000 miles of interstate and intrastate transmission pipelines (figure $16.2.m$). Compressor stations that maintain pressure on the natural gas to keep it moving through the system. There are more than 400 underground natural gas storage facilities that can hold the gas until it is needed back in the system for delivery.

Figure $16.2.m$: Construction of the controversial Dakota Access Pipeline, which stretches from North Dakota to Illinois. The pictured portion of the pipeline is in Central Iowa. You can learn more about the 2016 protests against this pipeline here. Image by Dakota Access Pipe Line (CC-BY).

Generating Electricity from Oil or Natural Gas

Natural gas is burned to produce electricity following the same general process used in a coal power plant (figure $16.2.n$). Oil is occasionally used to generate electricity as well.

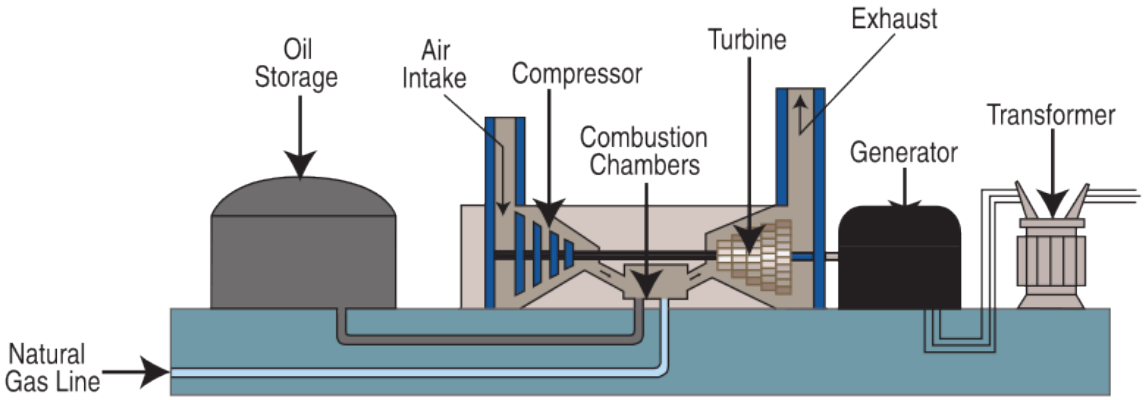

Figure $16.2.n$: This combustion chamber burns either natural gas or oil. Fuel flows through a natural gas line or from oil storage into the combustion chamber. Air passes through the air intake and is compressed in the compressor. Natural gas and compressed air are mixed with compressed air in the combustion chamber and burned. High-pressure combustion gases spin the turbine, which drives the generator. The resultant electric current is then passed through a transformer, which alters voltage. Image and caption (modified) by Tennessee Valley Authority (public domain).

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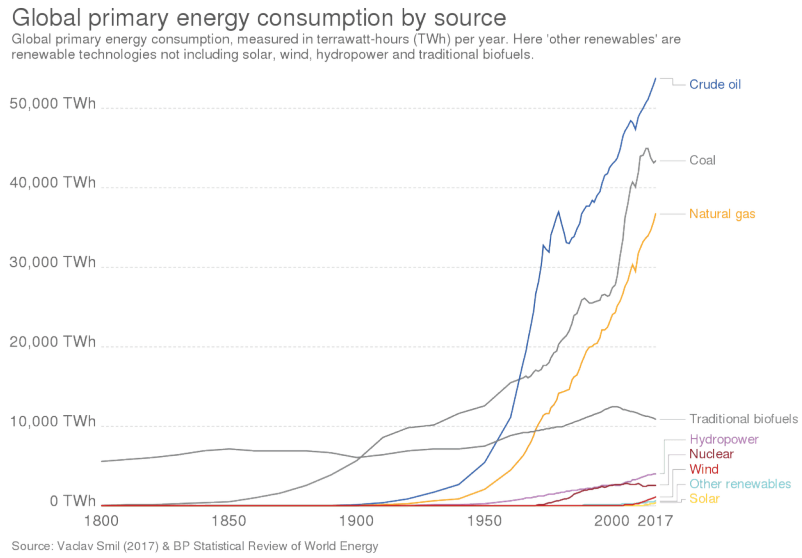
16.3: Fossil Fuel Consumption

The U.S. and the world overall heavily depend on fossil fuels. In 2019, fossil fuels contributed to 62.6% of electricity generation in the U.S. with coal contributing 23.4% and natural gas contributing 38.4% (table $16.3.a$). Note that oil (petroleum) is primary used for transportation and thus only contributes a fraction of a percentage to electricity generation. With respect to total energy consumption, the world continues to rely on crude oil more than any other energy source (33.1%) followed by coal (27%) and natural gas (24.3%; figure$16.3.a$).

Table $16.3.a$***:*** *Contribution of Each Energy Source to Electricity Generation in the U.S. in 2019*

Energy source	Contribution to Electricity Generation (%)
Fossil fuels (total)	**62.6%**
Natural gas	38.4%
Coal	23.4%
Petroleum (total)	0.4%
Other gases	0.3%
Nuclear	**19.6%**
Renewables (total)	**17.6%**
Hydropower	7.0%
Wind	7.1%
Biomass (total)	1.4%
Solar (total)	1.7%
Geothermal	0.4%

Table modified from U.S. Energy Information Administration (public domain).



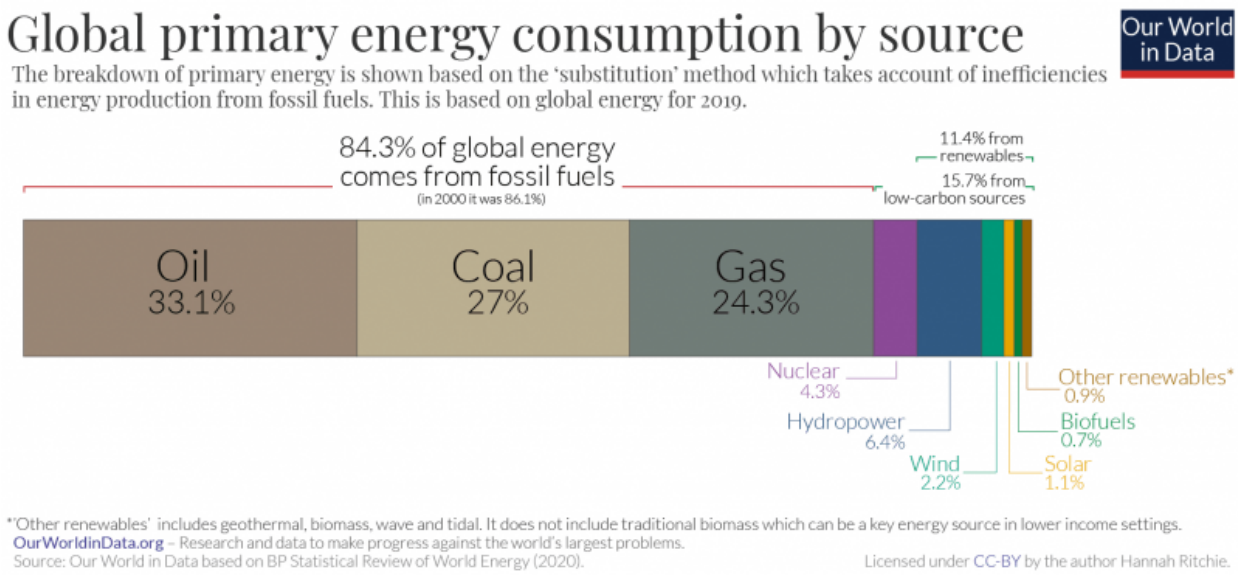


Figure $16.3.a$**:** The top graph shows global energy consumption by source shows energy consumption in terrawatt-hours (TWh) on the y-axis and time in years (1800-2017) on the X-axis. The bottom graph shows the percentage that each energy source contributes to global energy consumption in 2019. Global consumption of most energy sources has increased over time. Consumption of crude oil is the highest (33.1% of global energy consumption in 2019), and it increased rapidly in the 1950s, surpassing coal consumption in the early 1960s. Coal is now the second most-consumed energy source (27%), but its global consumption has declined in recent years. Natural gas is the third most-consumed energy source (24.3%) and has also been increasing. Coal and natural gas consumption surpassed that of traditional biofuels in the early 1900s and 1970, respectively. Nuclear energy consumption has decreased recently, accounting for 4.3% of global energy consumption in 2019. Consumption of renewable energy overall (11.4%) is low compared to fossil fuels (84.3% combined), but it has generally increased in recent years. Images by Our World in Data (CC-BY).

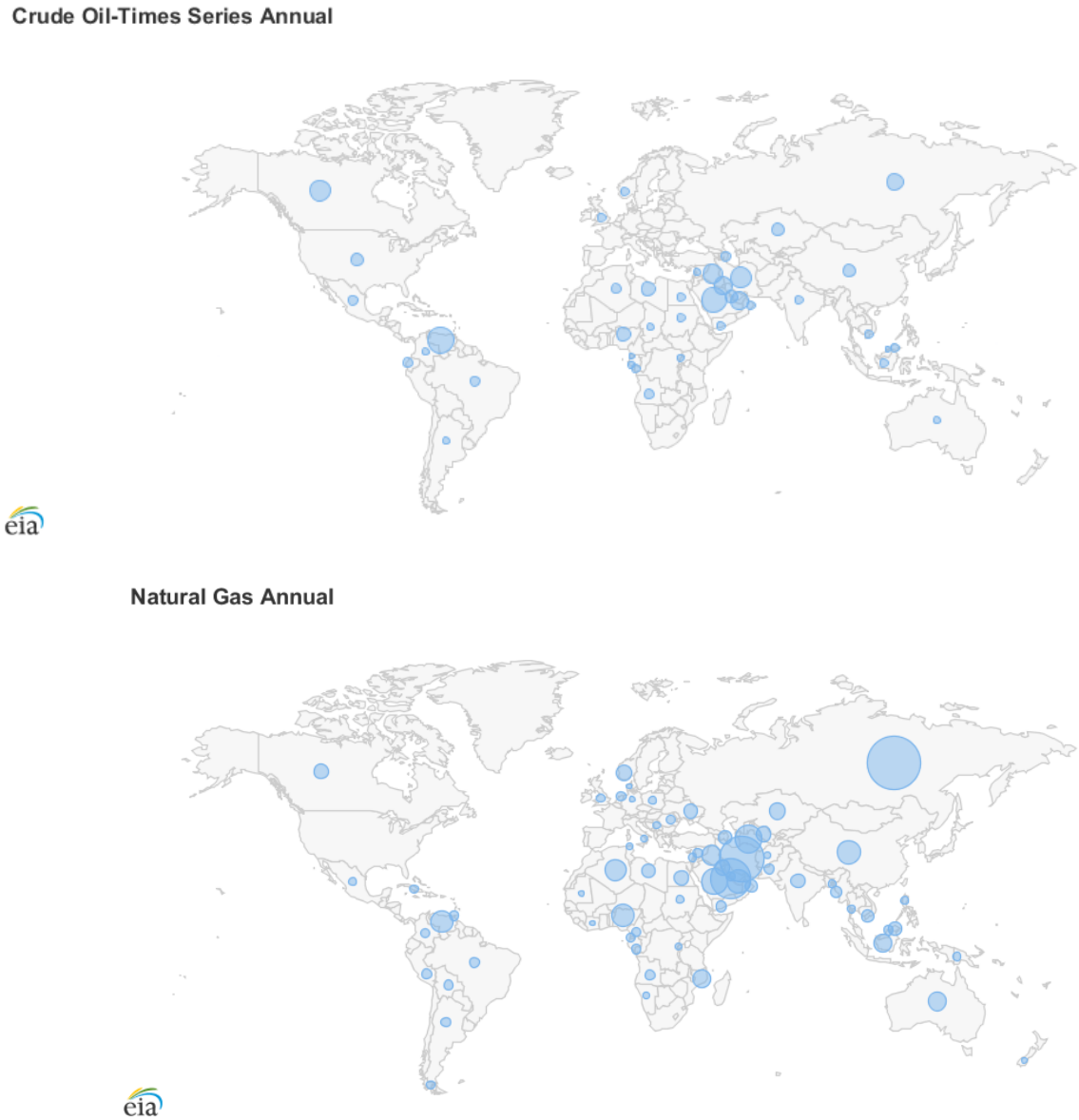
Coal has been used by humans for at least 6000 years, mainly as a fuel source. Coal resources in Wales are often cited as a primary reason for the rise of Britain (and later, the United States) in the Industrial Revolution. Coal electricity traces its origins to the early 20th Century, when it was the natural fuel for steam engines given its abundance, high energy density and low cost. Coal is the largest domestically produced source of energy. At the end of 2018, BP estimated at 734,903 million tonnes, with nearly 23.7% of that in the United States. It is a major fuel resource that the United States controls domestically.

Proven oil reserves (or natural gas reserves) refers to the amount of oil or natural gas that can be extracted economically with

current methods (such as conventional wells or fracking). The U.S. Energy Administration estimates that there are enough liquid fuels to last through 2050 (and they include biofuels in this projection). In 2016, BP projected that proven reserves of oil and natural gas can support global demands for another 50 years. Additionally, they estimate that coal reserves can last another 115 years.

Scientists and policy-makers often discuss the question of when the world will reach **peak oil production**, the point at which oil production is at its greatest and then declines. It was initially predicted that global peak oil would be reached in 2000, but oil production and consumption continue to rise. The United States, however, already passed peak oil production in 1970.

The concentration of oil reserves in a few regions of the world makes much of the world dependent on imported energy for transportation (figure$16.3.b$). The rise in the price of oil in the last decade makes dependence on imported energy for transportation an economic as well as an energy issue. The United States spent $304.9 billion on oil imports in 2019. The United States has become more and more dependent on foreign oil since 1970 when our own oil production peaked.



Figure$16.3.b$: Global reserves of oil (top) and natural gas (bottom) by country in 2017 and 2020, respectively. The blue circle in each country is scaled to the size of the reserve. Both fossil fuels are abundant in the Middle East. Russia also has a rich supply of natural gas. Images from EIA (public domain).

The major holder of oil reserves is the **Organization of Petroleum Exporting Countries,** (OPEC). As of 2024, there were 12 member countries in OPEC: Algeria, Congo, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Saudi Arabia, the

United Arab Emirates, and Venezuela. OPEC attempts to influence the amount of oil available to the world by assigning a production quota to each member except Iraq, for which no quota is presently set.

Overall compliance with these quotas is mixed since the individual countries make the actual production decisions. All of these countries have a national oil company but also allow international oil companies to operate within their borders. They can restrict the amounts of production by those oil companies. Therefore, the OPEC countries have a large influence on how much of world demand is met by OPEC and non-OPEC supply.

This pressure has lead the United States to developing policies that would reduce reliance on foreign oil such as developing additional domestic sources and obtaining it from non-Middle Eastern countries such as Canada, Mexico, Venezuela, and Nigeria. However, since fossil fuel reserves create jobs and provide dividends to investors, a lot is at stake in a nation that has oil reserves. Oil wealth may be shared with the country's inhabitants or retained by the oil companies and dictatorships, such as in Nigeria prior to the 1990s.

Attribution

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16.4: Consequences of Fossil Fuels

Benefits of Using Fossil Fuels

The world is heavily dependent on fossil fuels, and existing infrastructure and technologies facilitate their continued use. An advantage of using coal for electricity is that it plentiful and inexpensive, especially in the United States, which has larger coal reserves than any other country. Furthermore, coal mining is a source of jobs and tax income. Coal's economic advantage is dwindling, however, as technologies associated with renewable sources of energy, such as solar and wind, become more efficient and inexpensive. The U.S. Energy Information Administration compared the levelized cost of electricity (LCOE) for technologies that will begin use in 2023, and the cost of coal-generated electricity exceeded that of many renewable sources (figure $16.4.a$). The LCOE accounts for the building and operation costs of power plants, solar panels, wind turbines, etc.

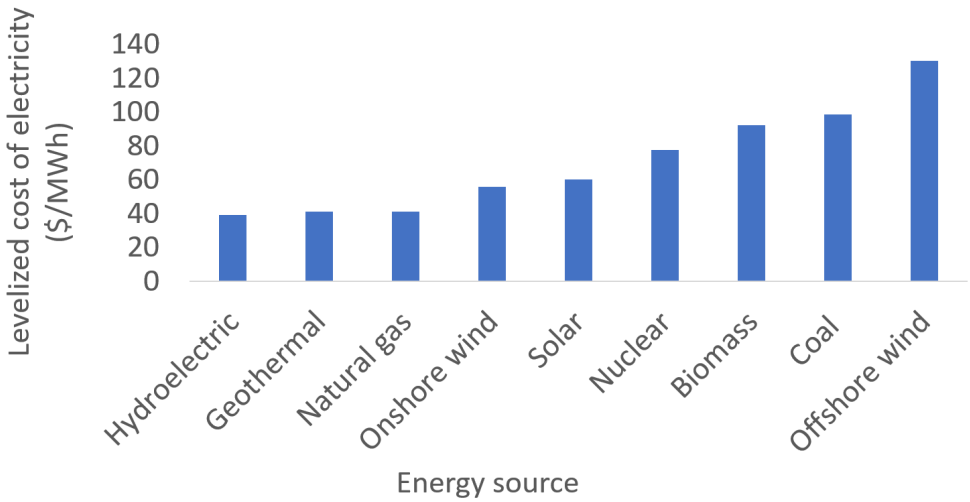

Figure $16.4.a$: The **levelized cost of electricity** (**LCOE**) for various energy sources. Of these, hydroelectric, geothermal, natural gas, onshore/offshore wind, solar, and biomass are considered renewable. Nuclear and coal are nonrenewable energy sources. Values are in 2018 dollars per **megawatt hour** ($/MWh). As a reference, the average U.S. household, uses about 0.909 MWh of electricity per month. These values are for the newest technologies that will being use in 2023. Hydroelectric energy is the least expensive, at about $39/MWh. Hydroelectric energy is the least expensive, at about $39/MWh. Next is geothermal ($41/MWh), natural gas ($41/MWh), onshore wind ($56/MWh), solar ($60/MWh), nuclear ($78/MWh), biomass ($92/MWh), coal ($99/MWh), and offshore wind ($130/MWh). Graph by Melissa Ha (CC-BY-NC) using data U.S. Energy Information Administration, Annual Energy Outlook 2019 (public domain).

Oil and natural gas continue to meet global energy needs. Despite expansions in renewable energy use, no alternative energy source is currently sufficient to replace oil and natural gas. (A combination of different renewable sources could be possible in the future.) While the United States does rely on imported oil, it continues to produce some oil and natural gas (mostly through fracking), bolstering U.S. energy independence. Local and state economics in regions rich in oil and natural reserves depend on continued extraction of these fossil fuels.

While all fossil fuels harm cause some degree of environmental harm, natural gas is a preferred fossil fuel for electricity generation when considering its environmental impacts. When burned, coal emits nearly double the carbon dioxide that natural gas does. Additionally, much less nitrogen oxides and sulfur dioxide (both air pollutants) are emitted from burning natural gas. It also does not produce ash as coal does (see below).

Health and Environmental Impacts

The negative impacts of fossil fuel use begin with the extraction of the resource. Fossils fuels are often located far from where they are utilized so they need to be transported by pipeline, tankers, rail or trucks. These all present the potential for accidents, leakage, and spills. Additional negative impacts are associated with processing, electricity generation, and disposal of the waste

generated.

Coal Mining and Usage

Surface mining of coal disrupts local ecosystems above coal deposits as overburden is removed to access them (figure $16.4.b$). In mountaintop removal, a large volume of overburden is dumped over nearby habitats, causing further destruction (figure $16.4.c$). Mountaintop removal has affected large areas of the Appalachian Mountains in West Virginia and Kentucky. Habitat loss from coal mining decreases biodiversity, resulting in a loss of ecosystem services. Both surface and subsurface mining expose rocks that can contain contaminants, such as heavy metals or sulfates, which them leach into streams or other bodies of water. This not only harms aquatic life, but it also disrupts nutrient cycling. One of the largest environmental impacts of subsurface mining may be the methane gas that must be vented out of mines to make the mines a safe place to work. Methane gas is a potent greenhouse gas and contributes to climate change. Finally, the process of mining ultimately compacts soil. This combined with the loss of trees, which slow the flow of run-off and promote infiltration, increases the risk of flooding.

Figure $16.4.b$: Peak Downs and Saraji Coal Mine in Queensland, Australia. To access the coal, vegetation was removed, destroying habitat for native organisms. Image by Lock the Gate Alliance (CC-BY).

Figure $16.4.c$: Mountaintop Removal Coal Mining in Martin County, Kentucky Photograph shows mountaintop coal removal mining in Martin County, Kentucky. Source: Flashdark.

Coal miners face health hazards such as explosions, mine collapse, and exposure to toxic fumes. **Black lung disease** is a

respiratory condition characterized by coughing and shortness of breath that occurs in miners exposed to too much coal dust. Residents near mines also risk exposure to coal dust and underground toxins following explosions. As a result of exposure to toxins, birth defects and other health problems are common in residents near mines.

Coal is considered the “dirtiest” source of energy because its combustion results in the most air pollution. Coal power plants emits a variety of air pollutants including sulfur dioxide, nitrogen oxide, and heavy metals. Sulfur dioxide and nitrogen oxide are sources of acid rain (acid deposition), smog, and health issues. Heavy metals cause neurological and developmental problems in humans and other animals. Burning of coal emits particulate matter and higher amounts of carbon dioxide per unit of energy than the use of oil or natural gas. Carbon dioxide is the most frequently emitted greenhouse gas and causes climate change. In 2018, electricity generation was responsible 27% of greenhouse gas emissions in the United States, and much of this was emitted from coal power plants. The transportation of coal usually relies on fossil fuels, releasing further pollution.

Ash (including fly ash and bottom ash) is a residue created when coal is burned at power plants. In the past, fly ash was released into the air through the smokestack, where it would contribute to particulate matter air pollution. Laws now require that much of the fly ash now must be be captured by pollution control devices, like scrubbers. In the United States, fly ash is generally stored at coal power plants or placed in landfills. Ash from storage or landfills can spill or leach into groundwater, resulting in water pollution.

Conventional Extraction Oil and Natural Gas

Exploring and drilling for oil degrades land and ocean habitats. On land, extensive infrastructure such as road networks, transport pipelines and housing for workers are needed to support a full-scale drilling operation. These can pollute soil and water, fragment habitats, and disturb wildlife. Extraction of oil and natural gas is also hazardous for workers, who have a high incidence of cancer and heart disease.

Human-caused oil spills in rivers and oceans harm ecosystems. From an economic perspective, oil spills disrupt the fishing industry and tourism. Oil spills at sea are generally much more damaging than those on land, since they can spread for hundreds of nautical miles in a thin oil slick which can cover beaches with a thin coating of oil. This can kill sea birds, mammals, shellfish and other organisms it coats. Oil spills on land are more readily containable if a makeshift earth dam can be rapidly bulldozed around the spill site before most of the oil escapes, and land animals can avoid the oil more easily.

Oil spills can result from supertanker accidents such as the Exxon Valdez in 1989, which spilled 10 million gallons of oil into the rich ecosystem of coastal Alaska and killed massive numbers of animals. The largest marine oil spill began in April 2010 when a natural gas explosion at an oil well 65 km offshore of Louisiana occurred on Deepwater Horizon Oil Rig. It killed 11 employees and flowed for 3 months in 2010, releasing an estimated 200 million gallons of oil (figure $16.4.d$). Wildlife, ecosystems, and people’s livelihood were adversely affected. A lot of money and huge amounts of energy were expended on immediate clean-up efforts. The long-term impacts are still not known. The National Commission on the Deepwater Horizon Oil Spill and Offshore Drilling was set up to study what went wrong. The worst oil spill ever occurred during the Persian Gulf war of 1991, when Iraq deliberately dumped approximately 200 million gallons of oil in offshore Kuwait and set more than 700 oil well fires that released enormous clouds of smoke and acid rain for over nine months.

Figure $16.4.d$: Platform supply vessels battle the blazing remnants of the off shore oil rig Deepwater Horizon. A Coast Guard MH-65C dolphin rescue helicopter and crew document the fire aboard the mobile offshore drilling unit Deepwater Horizon, while searching for survivors. Multiple Coast Guard helicopters, planes and cutters responded to rescue the Deepwater Horizon's 126 person crew. Image and caption (modified) from US Coast Guard (public domain).

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

Unconventional Extraction of Oil and Natural Gas

Fracking causes more environmental damage than conventional extraction. The considerable use of water (figure $16.4.e$) may affect the availability of water for other uses in some regions, and this can affect aquatic habitats. In fact, fracking consumes more water than the use of nuclear energy, coal, or conventional oil and natural gas. If mismanaged, hydraulic fracturing fluid can be released by spills, leaks, or various other exposure pathways that contaminate land and groundwater (figure $16.4.f$). Fracking fluid flowback – the fluid pumped out of the well and separated from oil and gas – not only contains the chemical additives used in the drilling process but also contains heavy metals, radioactive materials (which release radiation), volatile organic compounds, benzene (a carcinogen), toluene, ethylbenze, xylene, and other toxic air pollutants. Volatile organic compounds (VOCs) can react with the atmosphere to form ground-level ozone, which is associated with respiratory disease. Toulene can cause dizziness, confusion, headaches, and miscarriages. Ethylbenzene is a possible carcinogen that also causes dizziness, eye irritation, and hearing loss. Xylene also causes dizziness and headaches and furthermore can be fatal at high concentrations. In some cases, this contaminated water is sent to water treatment plants that are not equipped to deal with some of these classes of contamination. Finally, injecting wastewater for disposal can even induce earthquakes.

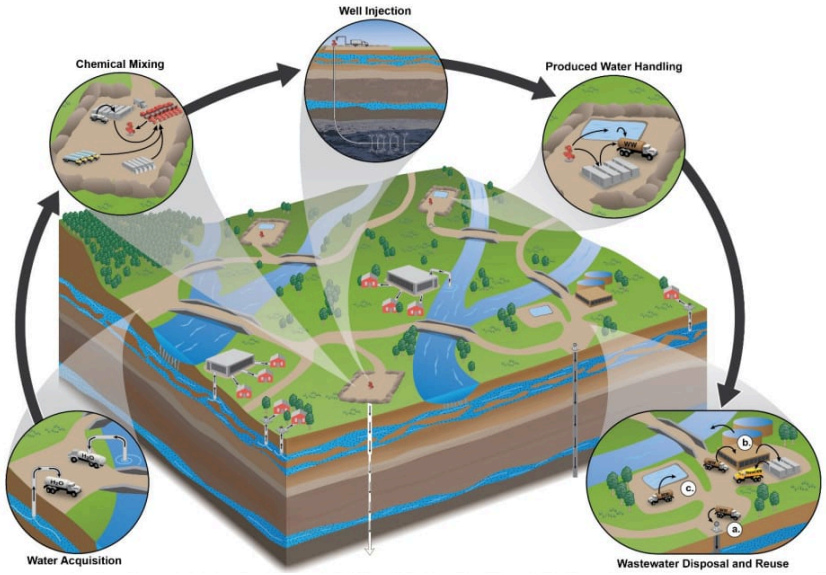

Figure $16.4.e$: Fracking influences the water cycle. Water acquisition is the withdrawal of groundwater or surface water to make hydraulic fracturing fluids. Chemical mixing involves combining a base fluid, sand, and additives at the well site to create hydraulic fracturing fluids. During well injection, hydraulic fracturing fluids move through the oil and gas production well and in the targeted rock formation. Produced water handling refers to the onsite collection and handling of water that returns to the surface after hydraulic fracturing and the transportation of that water for disposal or reuse. Finally, the disposal and reuse of wastewater occurs. If this is not done properly, wastewater can pollute surrounding areas. Image and caption (modified) by EPA (public domain).

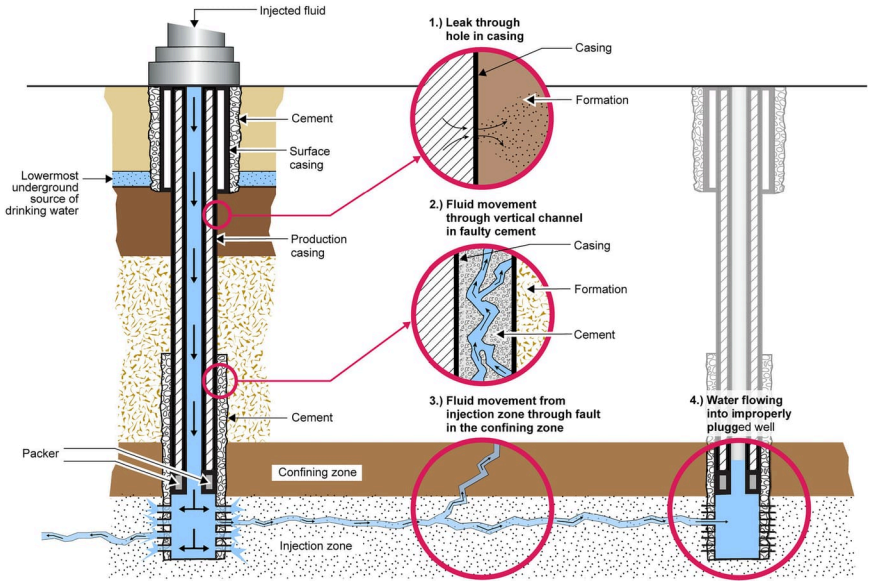

Figure $16.4.f$: The toxic fluid injected during fracking can escape, contaminating groundwater. For example, it can leak through a hole in the casing, move through faulty cement, or move through a fault in the rock that confines the deposit. Image by Government Accountability Office (public domain).

Other unconventional sources of fossil fuels can also harm the environment. Surface mining of tar sands or oil shales requires the removal of all vegetation and leaves pollutants behind, causing habitat loss (figure $16.4.g$).

Figure $16.4.g$: An open pit mine in the tar sands oil fields of Alberta, Canada. Conifer trees, which previously provided habitat to native animals, have been cleared to allow for mining. Image by Howl Arts Collective (CC-BY).

Transportation, Refineries, and Combustion

Natural gas is released into the atmosphere from coal mines, oil and gas wells, and natural gas storage tanks, pipelines, and processing plants. These leaks are the source of about 25% of total U.S. methane emissions, which translates to three percent of total U.S. greenhouse gas emissions, contributing to climate change. When natural gas is produced but cannot be captured and transported economically, it is "flared," or burned at well sites, which converts it to carbon dioxide. This is considered to be safer and better than releasing methane into the atmosphere because carbon dioxide is a less potent greenhouse gas than methane. However, when natural gas with high concentrations of the toxic gas hydrogen sulfide is flared, it produces carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen oxides, and many other compounds (see Air Pollution for more details).

Leaks also happen when we use petrochemicals on land. For example, gasoline sometimes drips onto the ground when people are filling their gas tanks, when motor oil gets thrown away after an oil change, or when fuel escapes from a leaky storage tank. When it rains, the spilled petrochemicals get washed into the gutter and eventually flow to rivers and into the ocean. Another way that oil sometimes gets into water is when fuel is leaked from motorboats and jet skis. When a leak in a storage tank or pipeline occurs, petrochemicals can also get into the ground, and the ground must be cleaned up. To prevent leaks from underground storage tanks, all buried tanks are supposed to be replaced by tanks with a double lining.

Oil refining emits a variety of toxins and is the single largest source of benzene (figure $16.4.g$). As a result, residents living near oil refineries have a high incidence of cancer, asthma, and birth defects. When petrochemicals such as gasoline or diesel are burned, they release a variety of air pollutants, including carbon dioxide (a cause of climate change), sulfur dioxide, nitrous oxides, volatile organic compounds (VOCs), particulate matter, and lead (see Air Pollution for more details). The transport of oil by ship or trunk also requires energy in the form of fossil fuels, generating more pollutants. Compared to oil and coal, burning natural gas releases the fewest pollutants and greenhouse gases.

Figure $16.4.g$: Pollutants are emitted from the Pine Bend oil refinery in Rosemount, Minnesota. Image by Tony Webster (CC-BY).

Solutions

Reclamation can mitigate the habitat damage that results from mining or extracting fossil fuels. It involves restoring the land to an extent after mining or extraction is complete. This can entail returning displaced land and covering with top soil, which protects organisms from heavy metals, radioactive materials, and other underground toxins. Additionally, acids, which often form from the leaching of sulfates from underground rocks, may be neutralized. Vegetation is then planted, and water flow if disrupted is somewhat restored. Of course, the intricate topography, network of streams, and mature vegetation (such as large trees in forest) that may have been present prior to mining cannot be recreated, but reclamation makes it easier for native species to begin recolonizing the area.

Clean coal technologies can limit the air pollution released when burning coal. Some of these technologies remove toxins from coal before burning it while others capture toxins that are released while burning coal. For example, **smokestack scrubbers** in power plants clean sulfur dioxide, nitrous oxide, particulate matter, and mercury from the smoke before it is released. **Carbon capture and sequestration** involves capturing carbon dioxide released and storing it, but it requires 25-40% more energy, reducing the efficiency of coal (figure $16.4.h$). In this process, smoke from a coal power plant is passed through a solvent to trap carbon dioxide, but other waste gases are still released in the smoke. Carbon dioxide is then separated from the solvent. Some can be used in industry (such as for carbonated beverages or to tertiary recovery of oil), and the rest is sequestered (stored) underground. Note that clean coal technologies can reduce coal's contribution to climate change and reduce the amount of toxins that are released, but it does not fully prevent coal-generated air pollution (figure $16.4.i$).

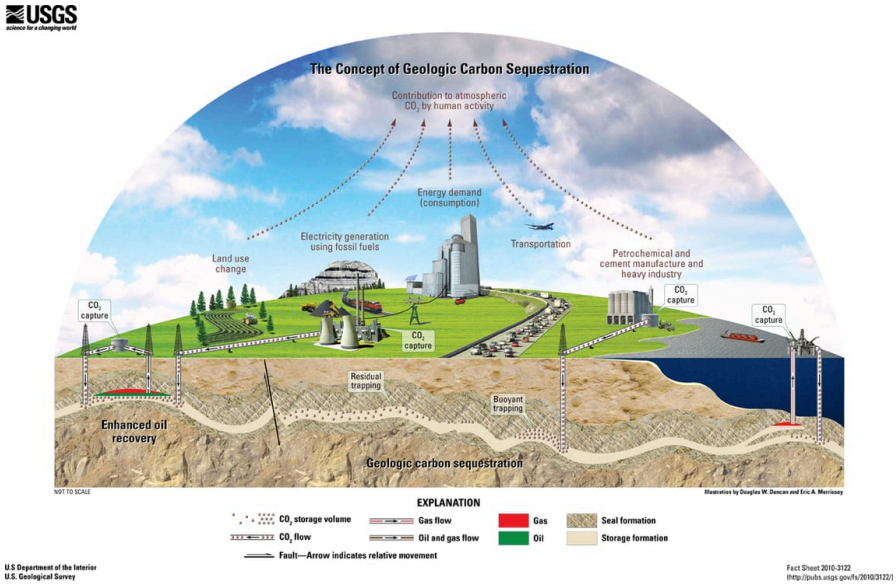

Figure $16.4.h$: Burning fossil fuels releases carbon dioxide into the atmosphere, but there are also opportunities to sequester (store) carbon dioxide, offsetting some fo this damage. Some of the carbon dioxide injected during tertiary recovery (enhanced oil recovery) remains underground. Additionally, carbon dioxide may be captured from smoke released by power plants and other industries and stored under ground. Image by USGS (public domain).

Figure $16.4.i$: A protest against clean coal at the United Nations Climate Change Conference (COP19) in 2013. Image by 350.org (CC-BY-NC-SA).

Because fossil fuels are nonrenewable, reserves will eventually be depleted, and the world will need to fully rely on other energy sources. Those concerned about the environmental and health consequences of fossil fuels advocate for making this transition as soon as possible. This is because the technologies and practices discussed above do not fully prevent fossil fuels from causing environmental damage and causing health hazards for workers and the general public. The next two chapters discuss nuclear energy and renewable energy, which are alternatives to fossil fuels. As even these alternatives have their disadvantages, **energy conservation** (using energy more efficiently and limiting unnecessary energy use) is also critical.

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16.5: Data Dive- Global Fossil Fuel Consumption

Overview

Our World in Data (OWID) is a scientific online publication that focuses on using research and data to help tackle global concerns such as poverty, disease, hunger, climate change, war, and inequitable treatment of our world's most vulnerable and unstable communities. Their website is particularly known for publishing a variety of graphs, some even interactive, to present the research that helps explain causes and consequences of global concerns to the public. One example graph, seen below, illustrates global fossil fuel consumption:

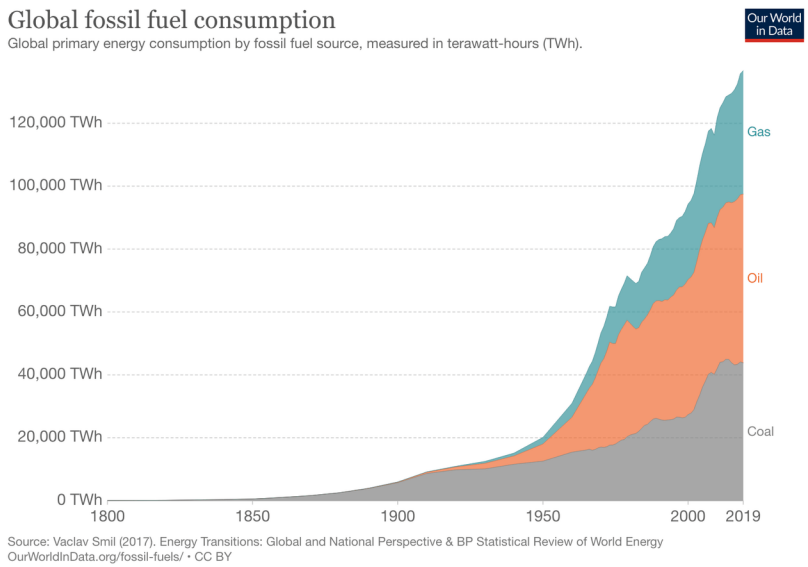

Figure $16.5.a$: Global consumption of gas, oil, and coal. Graph by Our World in Data (CC-BY)

Questions

1. What kind of graph is this?
2. What question(s) are the authors trying to answer with this graph?
3. What are the observed patterns of fossil fuel use (gas, oil, and coal) in this graph?
4. Make a prediction for each fossil fuel use pattern for the next 50 years. For each prediction, state why you think that pattern will occur.
5. How do you think climate scientists are using a graph like this to predict climate into the future?

Raw Data For Above Graph(s)

Raw data table link to Our World in Data graph above. (CC-BY)

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16.6: Review

Summary

After completing this chapter you should be able to...

- Distinguish among coal, oil, and natural gas and explain how each is formed.
- Describe the processes of mining, processing, transporting, and burning coal to produce electricity.
- Compare the processes of conventional oil and natural gas extraction and fracking.
- Identify the relative contributions of coal, oil, and natural gas to electricity generation in the U.S. and total energy consumption globally.
- Detail the advantages and disadvantages of fossil fuel use.
- Describe strategies to mitigate harm caused by fossil fuel use.

Fossil fuels are nonrenewable energy sources that were formed from ancient organisms. **Coal** is a solid fossil fuel formed from ancient swamp vegetation. **Oil** (petroleum) and natural gas both formed from marine microorganisms and are often found together; however, oil is a liquid fossil fuel, and natural gas is in gaseous form.

Coal is produced through **surface** and **subsurface mining**. Some oil and natural gas reserves can be recovered through **conventional extraction**, but unconventional reserves are recovered through **hydraulic fracturing** (tight oil and natural gas; tight sands) or mining (oil shale and tar sands). To produce electricity from coal or natural gas, the fuel is combusted (burned). The heat is used to produce steam, and the pressure from the steam turns a turbine, which powers a generator. **Crude oil** must be refined to separate it into a variety of **petrochemicals**, each with a different use.

Nationally and globally, fossil fuel consumption remains high. **Proven reserves** of oil and natural gas are projected to last another 50 years while coal reserves are projected to last another 115 years. The U.S. has a large supply of the world's coal but relies largely on imports to meet its oil demands. The world's oil supply is concentrated in OPEC countries, which have great influence over global rates of production.

While existing technologies facilitate continued fossil fuel use, which support local and national economies, fossil fuels cause a variety of health and environmental consequences. Workers and those living near mines or oil refineries are at the greatest risk of health consequences, but combustion of fossil fuels releases air pollutants that harm the general public and native organisms. Furthermore, mining, drilling, and fracking, destroy habitats and release pollutants. **Clean coal technologies** and **reclamation** reduces but does not eliminate these negative consequences.

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18: RENEWABLE ENERGY

Chapter Hook

City water pipes, an unlikely place to be a source electricity. Yet, Portland Oregon has decided to set up hydroelectric turbines in the cities drinking water pipes. This provides around the clock local energy that doesn't affect natural waterways as classic hydroelectric turbines do. This setup is the first of its kind in the United States and truly exemplifies the objectives that renewable energies aspire to achieve.

Figure 18.a: Water turbine example. Image by Pixabay (Public Domain)

18.1: Renewable Energy History and Consumption

18.2: Wind Energy

19.3: Solar Energy

18.4: Geothermal Energy

18.5: Hydropower

18.6: Biofuels (Biomass Energy)

18.7: Energy Conservation

18.8: Data Dive- Global Renewable Energy Generation

18.9: Review

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18.1: Renewable Energy History and Consumption

Renewable energy sources can be replenished within human lifespans. Although renewable energy is often classified as **wind**, **solar**, **geothermal**, **hydropower** (hydroelectric energy/hydroelectricity), and **biofuels** (**biomass energy**), all forms of renewable energy arise from only three sources: the light of the sun (wind, solar, hydropower, and biofuels), the heat of the earth's crust (geothermal), and the gravitational attraction of the moon and sun (**tidal energy**; figure $18.1.a$). Sunlight provides by far the largest contribution to renewable energy. The sun provides the heat that drives the weather, including the formation of high- and low-pressure areas in the atmosphere that make wind. The sun also generates the heat required for vaporization of ocean water that ultimately falls over land creating rivers that drive hydropower, and the sun is the energy source for photosynthesis, which creates biomass. The sun is also responsible for the energy of fossil fuels, created from the organic remains of plants and sea organisms compressed and heated in the absence of oxygen in the earth's crust for tens to hundreds of millions of years. The time scale for fossil fuel regeneration, however, is too long to consider them renewable in human terms.

Figure $18.1.a$: A tidal current energy generator at Race Rocks in British Columbia, Canada. Image by Garry Fletcher (CC-BY-SA).

Most renewable energy sources have a relatively **small carbon footprint**, meaning that they do not significantly contribute to climate change. However, building dams for hydropower (hydroelectric energy) does release methane, a potent greenhouse gas. Renewable energy sources are pollution free (except biofuels), and they typically have minimal environmental impact (except habitat loss from dams). Up to this point, however, no single source of renewable energy is sufficient. They generally are paired with other energy sources.

Strong interest in renewable energy in the modern era arose in response to the oil shocks of the 1970s, when the Organization of Petroleum Exporting Countries (OPEC) imposed oil embargos and raised prices in pursuit of geopolitical objectives. The shortages of oil, especially gasoline for transportation, and the eventual rise in the price of oil by a factor of approximately 10 from 1973 to 1981 disrupted the social and economic operation of many developed countries and emphasized their precarious dependence on foreign energy supplies. The reaction in the United States was a shift away from oil and gas to plentiful domestic coal for electricity production and the imposition of fuel economy standards for vehicles to reduce consumption of oil for transportation. Other developed countries without large fossil reserves, such as France and Japan, chose to emphasize nuclear (France to the 80% level and Japan to 30%) or to develop domestic renewable resources such as hydropower and wind (Scandinavia), geothermal (Iceland), solar, biomass and for electricity and heat. As oil prices collapsed in the late 1980s, interest in renewables, such as wind and solar that faced significant technical and cost barriers, declined in many countries. Other renewables, such as hydropower and biomass, continued to experience growth. As climate change worstens, the solar and wind energy has expanded globally in recent years.

Renewable energy accounted for 11.4% of total global energy consumption and 26.3% of global electricity generation in 2019 (figure $18.1.b$). In the United States, renewable energy also accounted for about 11% of total energy consumption but only 17.6% of electricity generation. Nearly half (43%) of total renewable energy use in the U.S. is from biofuels. For electricity generation in

the U.S., wind was the greatest contributor (7.1%) followed by hydropower (7.0%), solar (1.7%), biomass (1.4%), and geothermal (0.4%).

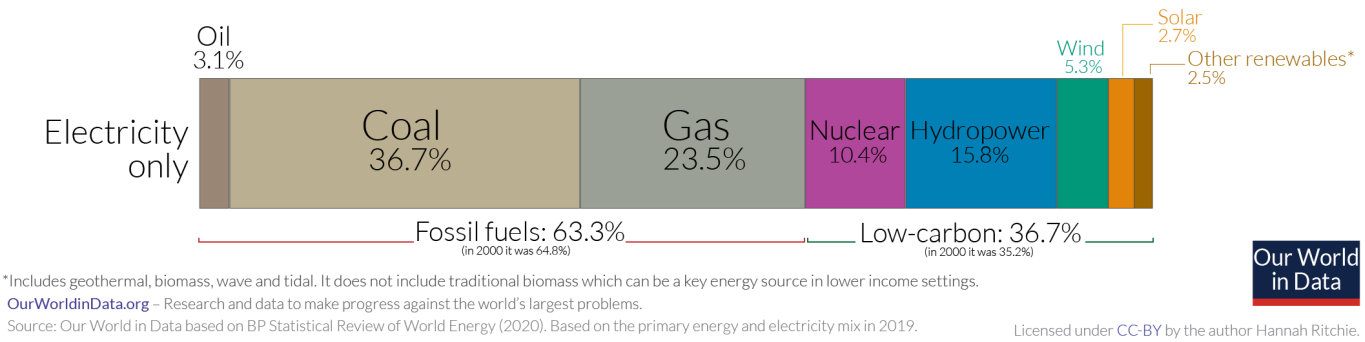

Figure 18.1.b: The global electricity breakdown in 2019. Renewables accounted for 26.3% of global electricity generation, with hydropower accounting for 15.8% followed by wind (5.3%), solar (2.7%), and other renewables (2.5%; geothermal, biomass, wave, and tidal). Fossil fuels accounted for 63.3% of global electricity generation, including oil (3.1%), coal (36.7%), and gas (23.5%). For comparison, fossil fuels accounted for 64.8% of global electricity generation in 2000. Nuclear accounted for 10.4% of global electricity generation. Nuclear and renewables combined are considered low-carbon electricity sources, together accounting for 36.7% of electricity generation. For comparison, low-carbon sources accounted for 35.2% of electricity generation in 2000. Image modified from Hannah Ritchie/Our World in Data (CC-BY).

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18.2: Wind Energy

Wind energy arises from the motion of the air. It is driven by solar energy (differences in air temperature causes air currents). The wind turns a turbine, which powers a generator (figure $18.2.a$). The rotor blades of a wind turbine work like an airplane wing or helicopter rotor blade. When wind flows across the blade, the air pressure on one side of the blade decreases, and this causes the rotor to spin. The rotor connects to the generator, either directly or through a series of gears that speed up the rotation and allow for a physically smaller generator. Similar to the electricity generation from coal, natural gas, or nuclear energy, the rotating motion causes magnets spin within wire coils to produce electricity. According to the American Wind Energy Association, 39% of all new electrical generating capacity in the United States in 2019 was due to wind.

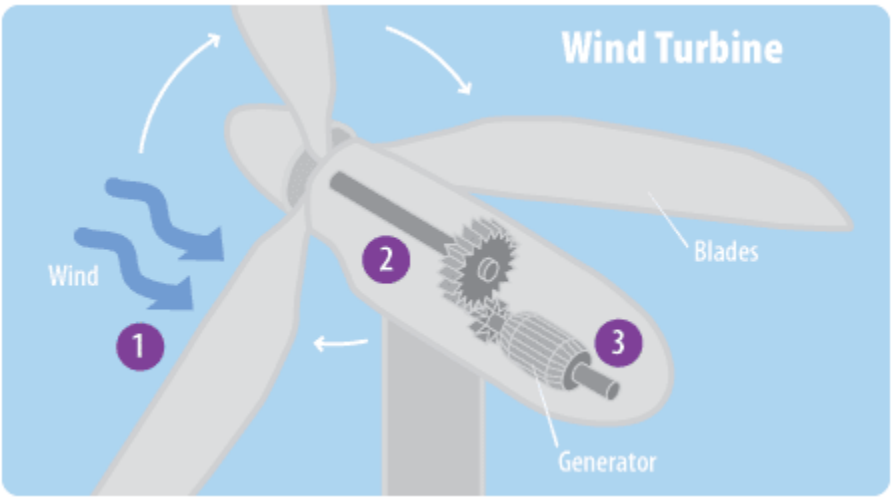

Figure $18.2.a$: (1) As the wind blows over the blades of a wind turbine, it causes the blades to lift and rotate. (2) The rotating blades turn a shaft that is connected to a generator. (3) The generator creates electricity as it turns. Image and caption (modified) from EPA (public domain).

Interactive Element

Click here for an interactive animation illustrating how wind turbines work.

Advantages of Wind Energy

Wind is among the lowest-cost sources of renewable energy, and its expansion creates jobs (figure $18.2.b$). Like many renewable energy sources, wind turbines do not release air pollutants or contribute to climate change, and they do not require water for cooling. Because a wind turbine has a small physical footprint relative to the amount of electricity it produces, many wind farms are located on crop and pasture land. They contribute to economic sustainability by providing extra income to farmers and ranchers, allowing them to stay in business and keep their property from being developed for other uses. For example, energy can be produced by installing wind turbines in the Appalachian mountains of the United States instead of engaging in mountain top removal for coal mining. Offshore wind turbines on lakes or the ocean may have smaller environmental impacts than turbines on land, and winds are up to 50% stronger and steadier offshore than on land (figure $18.2.c$).

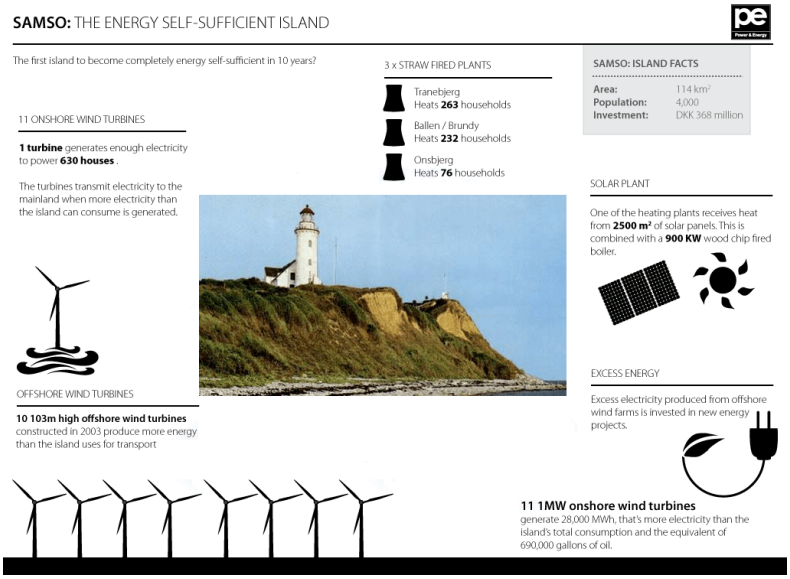

Figure $18.2.b$: The Danish island of Samsø was the first region in the country to transition to 100% renewable energy, relying on offshore wind, onshore wind, straw (a biofuel), and solar. The text in the image is, "Samsø : The Energy Self-sufficient Island. The first island to become complete energy self-sufficient in 10 years. Samsø: Island Facts— Area: 114 km^2, Population: 4,000, Investment: DKK 368 million. 11 Onshore Wind Turbines— 1 turbine generates enough electricity to power 630 houses. The turbines transmit electricity to the mainland when more electricity than the island can consume is generated. Offshore Wind Turbines- 10 103-m-high offshore wind turbines constructed in 2003 produce more energy than the island uses for transport. 11 1-MW Onshore Wind Turbines generate 28,000 MWh. That's more electricity than the island's total consumption and the equivalent of 690,000 gallons of oil. 3X Straw-fired Plants— Traneberg- heats 263 households, Ballen/ Brundy- heats 232 households, Onsbjerg- heats 76 households. Solar Plant- One of the heating plants receives heat from 2500 m^2 of solar panels. This is combined with a 900 KW wood chip-fired boiler. Excess Energy- Excess electricity produced from offshore wind farms is invested in new energy projects. Images by GDS Infographics (CC-BY) and National Geospatial-Intelligence Agency (public domain).

Figure 18.2.b: Wind turbines may be on land (onshore, left) or in the ocean (offshore, right). Left image by Joshua Winchell/USFWS (public domain). Right image by CGP Grey (CC-BY).

Disadvantages of Wind Energy

Wind energy does have a few challenges. Wind turbines are only effective in regions with strong enough winds to generate sufficient electricity. Even in regions with strong winds, wind availability is intermittent. This can be mitigated by the use batteries to store energy, but battery capacity, despite continuous technological advances, is still limited. There are aesthetic concerns to some people when they see them on the landscape, and some people do not like the sound that wind turbine blades make. A few wind turbines have caught on fire, and some have leaked lubricating fluids, though this is relatively rare. Turbines have been found to cause bird and bat deaths particularly if they are located along their migratory path, although communication towers and domestic cats are bigger threats. There are some small impacts from the construction of wind projects or farms, such as the construction of service roads, the production of the turbines themselves, and the concrete for the foundations.

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19.3: Solar Energy

Solar energy refers to heat or light energy from the sun. Solar energy is by far the most plentiful type of renewable energy, delivered to the surface of the Earth at a rate of 120,000 Terawatts (TW) per hour, compared to the global human use of 19.8 TW in the entire year of 2019. To put this in perspective, covering 1.2% of the Sahara desert with solar panels could meet Earths energy needs. Of course, this does not consider limitations on storage capacity and the ability to distribute that energy.

Technologies to harness solar energy may be passive or active. **Passive solar technologies** do not require complex equipment and can be as simple as using natural light from a window or skylight to illuminate a room (figure $19.3.a$). Similarly, solar tubes are lined with reflective material and can concentrate light energy to better illuminate a room (figure $19.3.a$). These are embedded in the ceiling as regular light fixtures would be.

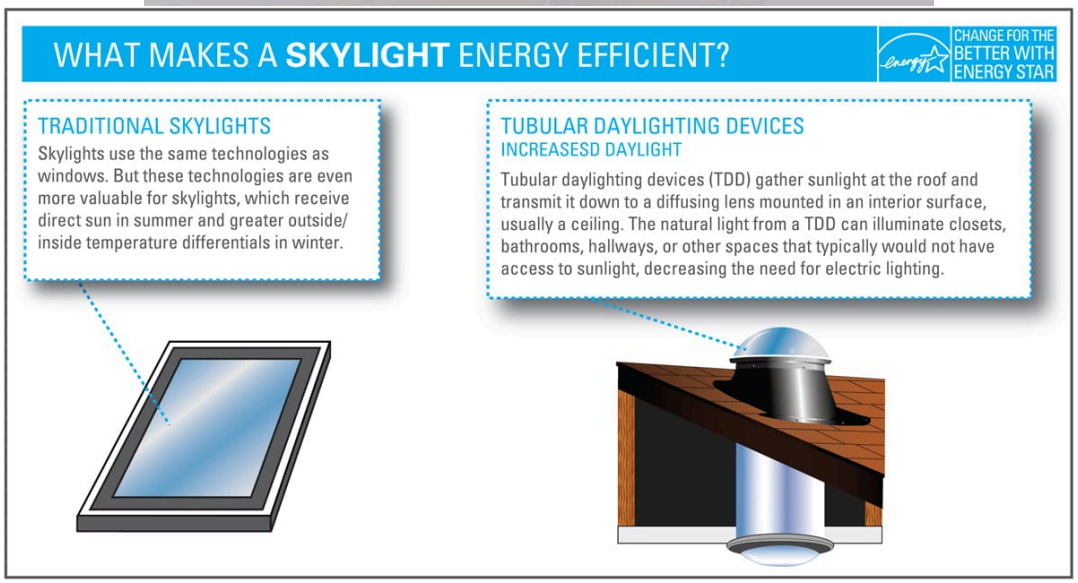

Figure $19.3.a$: Skylights and solar tubes (tubular daylighting devices, TDD). While skylights resemble windows that are installed in the ceiling, solar tubes use lenses and a reflective lining to concentrate sunlight, providing bright illumination for darker parts of the home. What makes a skylight energy efficient? Traditional skylights are skylights that use the same technologies as windows, but these technologies are even more valuable for skylights, which receive direct sun in summer and greater outside/inside temperature differentials in winter. Tubular daylighting devices gather sunlight at the roof and transmit it down to a diffusing lens mounted in an interior surface, usually a ceiling. The natural light from a TDD can illuminate closets, bathrooms, hallways, or other spaces that typically would not have access to sunlight, decreasing the need for electric lighting. Left image by U.S. Department of Energy (public domain), and right image by Energy Star (public domain).

Solar energy can also be used as heat, which can be maximized through careful architecture (figure $19.3.b$). Firstly, the building requires south-facing windows (or glass doors). As sunlight passes through these areas, the energy is stored in the thermal mass of the building. This refers to heat trapping materials such as rock or tiles. The building is also designed such that heat is then distributed throughout the building. Finally, roof eaves or similar structures block sunlight from entering the home during the summer.

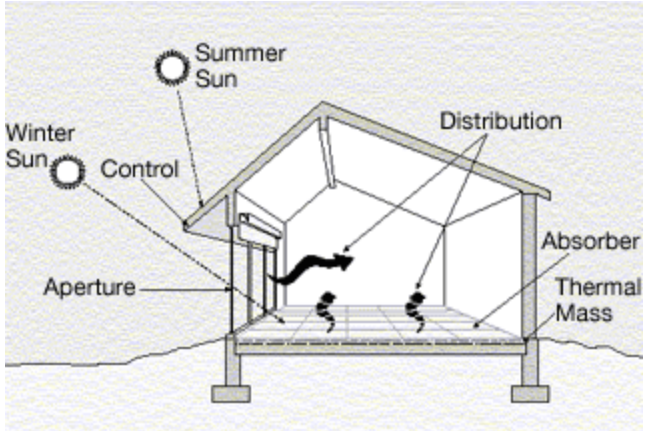

Figure $19.3.b$: This building design uses the sun for heating during the winter and is thus a passive solar technology. The roof overhang serves as a control, blocking the higher summer sun while allowing the lower winter sunlight to pass through the window (aperture). Heat energy from the sun is then distributed in the building. Thermal mass (such as a tile or stone floor) absorbs and later releases heat energy. Image by U.S. Department of Energy (public domain).

A simple solar water heater is a passive technology consisting of a network of tubes that are heated by the sun (figure $19.3.c$). The hot water is then transferred through the plumping of a home. (Some solar water heaters are more complex, using pumps, and are thus considered active solar technologies.)

Figure $19.3.c$: A solar water heater. Image by Vijayanarasimha/Pixabay (public domain).

Active solar technologies are more complex. For example, solar panels use light energy to generate electricity (figure$19.3.d$). This occurs in the units of the solar panel, which are called **photovoltaic cells** (PV cells; figure$19.3.e$). Each photovoltaic cell consists of two layers of **semiconductors**, substances that only conduct electricity under certain circumstances. (In contrast, conductors always conduct electricity, and insulators do not.) One semiconductor has extra electrons, but the other has extra spaces for electrons. When light shines on the photovoltaic cell, it causes electrons to move from between semiconductor layers through the conductor that connects them (such as metal wires or plates). This movement results in an electric current.

Figure $19.3.d$: Rooftop solar installation on Douglas Hall at the University of Illinois at Chicago has no effect on land resources, while producing electricity with zero emissions. Source: Office of Sustainability, UIC

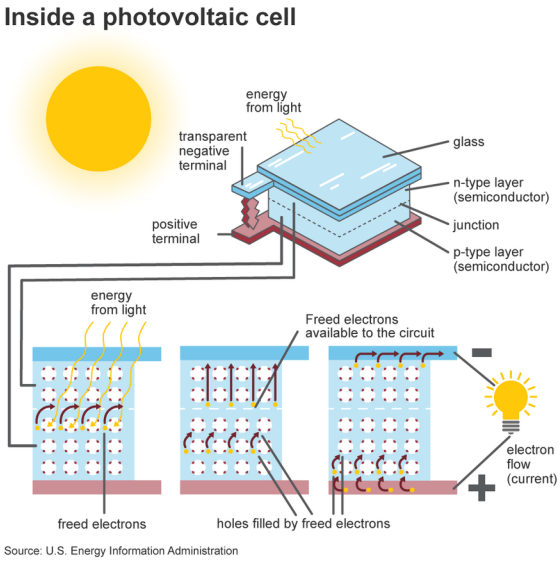

Figure $19.3.e$: Diagram of a **photovoltaic cell** consisting of two layers of semiconductors. The top (n-type) semiconductor has extra electrons and the bottom (p-type) semiconductor has extra spots (holes) for electrons. A junction divides these two layers. Light frees the electrons and allows them to move through a wire from the n-type to fill "electron holes" in the p-type semiconductor. The movement of electrons through the wire results in an electrical current. Image by U.S. Energy Information Administration (public domain).

This video explains how the photovoltaic cells within solar panels generate electricity.

YouTube Video

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Another example of active solar technology is **solar thermal technology**. This involves using a series of mirror to concentrate

solar energy, ultimately generating steam. From there, the steam turns a turbine and powers a generator (figure$19.3.f$).

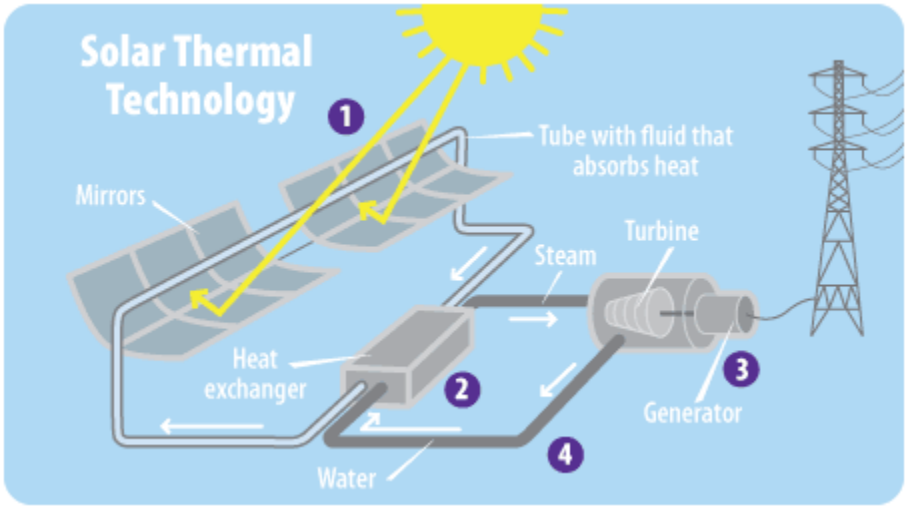

Figure $19.3.f$: In solar thermal technology, (1) mirrors or reflectors concentrate the sun's rays to heat a special kind of liquid, which absorbs heat. (2) The heat from this liquid boils water to create steam, facilitated by the heat exchanger. (3) Steam spins a turbine that is connected to a generator, which creates electricity. (4) The steam cools and condenses back to water, which is recycled, reheated, and converted into steam again. Image and caption (modified) from EPA (public domain).

Not only is solar energy abundant, but the use of solar panels for electricity does not generate air pollution or contribute to climate change. (The manufacture of solar panels can generate some pollution, including greenhouse gas emissions, but this is minimal compared to that of fossil fuels.) Like wind energy, expansions on solar energy can create jobs and boost economies. Also like wind, sunlight is intermittent and storage of solar energy is limited by battery capacity. Some locations do not receive consistently direct sunlight and are ill-suited for solar panels. While solar energy has historically been the most expensive form of renewable energy, new technologies have lowered its cost.

The placement of solar panels determines how their environmental impact. Solar arrays are often placed on roofs of buildings or over parking lots or integrated into construction in other ways. However, large systems may be placed on land and particularly in deserts where those fragile ecosystems could be damaged if care is not taken. Additionally, solar farms can compete for agricultural space.

Other downsides of solar energy are water consumption (for some uses) and generation of hazardous wastes. Large networks of mirrors and lenses that concentrate solar energy for electricity generation in thermal solar systems or for heating may need to be cleaned regularly with water. Water is also needed for cooling the turbine-generator. Using water from underground wells may affect the ecosystem in some arid locations. The manufacturing of photovoltaic cells generates some hazardous waste from the chemicals and solvents used in processing. Some solar thermal systems use potentially hazardous fluids (to transfer heat) that require proper handling and disposal. Nuclear power exceeds solar energy in water consumption and hazardous waste generation, however.

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18.4: Geothermal Energy

Geothermal energy originates from heat rising to the surface from Earth's molten iron core created during the formation and compression of the early Earth as well as from heat produced continuously by radioactive decay of uranium, thorium, and potassium in the Earth's crust. **Geothermal power plants** harness this heat energy to produce electricity much in the same way that heat from burning coal generates energy (figure $18.4.a - c$). Water is injected underground and heated. The steam that emerges can be used directly, the heat can be transferred to closed system of another fluid, which then boils (figure $18.4.c$). Either way, the steam (or other high-pressure gas) ultimately turns a turbine and powers a generator.

Figure $18.4.a$: Steam is released from a geothermal power plant. Image by Open Access Government (CC-BY).

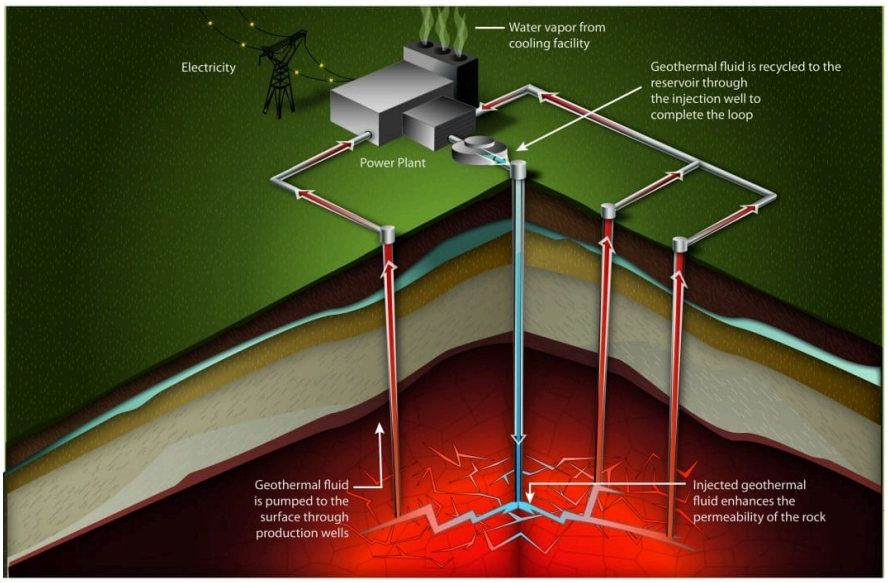

Figure $18.4.b$: In a geothermal power plant, geothermal fluid is injected underground. (Geothermal water refers to the hot water/steam used in this process.) It enhances the permeability of the rocks and is heated underground. It exits to the surface through production wells, where it is used to generate electricity in the geothermal power plant. Water vapor is released from the cooling facility of the power plant. To recycle the geothermal fluid, it is returned to the reservoir and injected back into the ground. Image from Office of Energy Efficiency and Renewable Energy/U.S. Department of Energy (public domain).

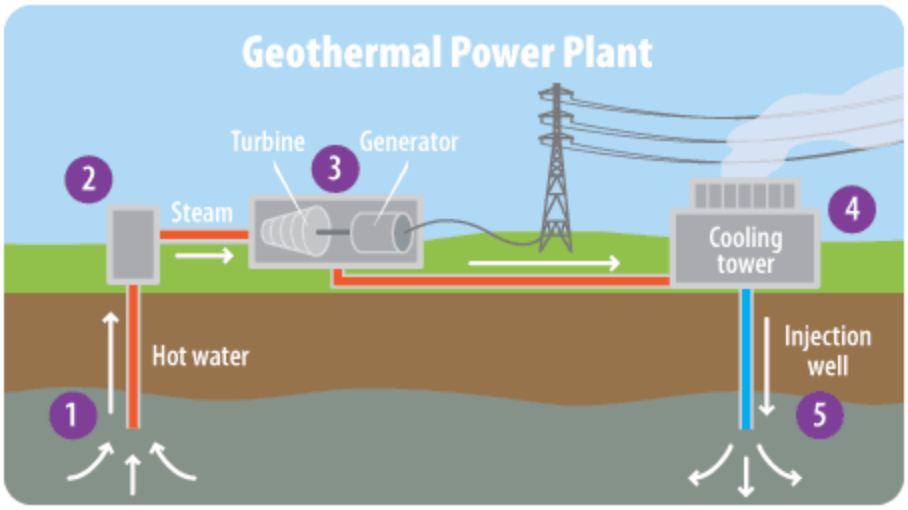

Figure 18.4.c: (1) In a geothermal power plant, hot water is pumped from deep underground through a well under high pressure. (2) When the water reaches the surface, the pressure is dropped, which causes the water to turn into steam. (3) The steam spins a turbine, which is connected to a generator that produces electricity. (4) The steam cools off in a cooling tower and condenses back to water. (5) The cooled water is pumped back into the Earth to begin the process again. Image and caption (modified) from EPA (public domain).

Geothermal heat pumps (**ground-source heat pumps**) rely on cool temperatures underground to cool or heat homes (figure 18.4.d). They are sometimes considered a second type of geothermal energy, but they are also a means of energy conservation. Geothermal heat pumps use a heat-exchange system that runs in the subsurface about 20 feet (5 meters) below the surface, which is consistently cool (around 55°F, or 12.5° C). Fluid is pumped underground and then along ducts in the home. This cools the house during the summer, acting as a heat sink. During a cold winter, it warms the house to 55° F (acting as a heat source), and traditional heating systems do the rest. This reduces the energy consumption required to generate heat from gas, steam, hot water, and conventional electric air-conditioning systems.

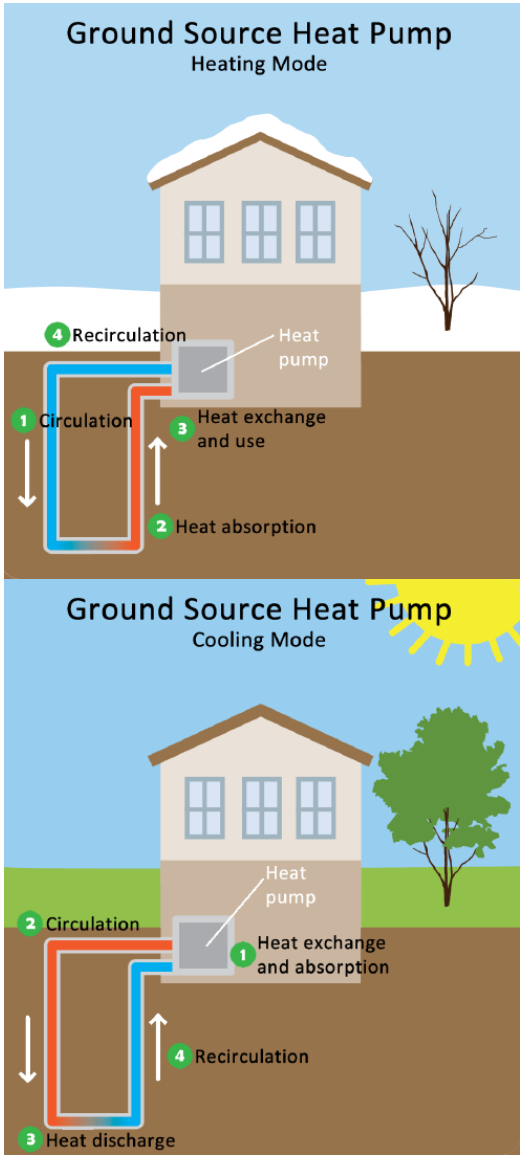

Figure 18.4.d: A ground source heat pump (geothermal heat pump) in heating mode (during the winter; left) and in cooling mode (during the summer; right). There are four steps for heating mode (left). (1) Circulation: The above-ground heat pump moves water or another fluid through a series of buried pipes or ground loops. (2) Heat absorption: As the fluid passes through the ground loop, it absorbs heat from the warmer soil, rock, or ground water around it. (3) Heat exchange and use: The heated fluid returns to the building where it used for space or water heating. The system uses a heat exchanger to transfer heat into the building's existing air handling, distribution, and ventilation system. (4) Recirculation: Once the fluid transfers its heat to the building, it returns at a lower temperature to the ground loop to be heated again. This process is repeated, moving heat from one point to another. The four steps for cooling mode (right) are similar: (1) heat exchange and absorption, (2) circulation, (3) heat discharge, and (4) recirculation. Images and caption (modified) from EPA (public domain).

This video explains the construction and mechanism of geothermal heat pumps.

YouTube Video

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Not only does geothermal energy have multiple applications (generating electricity, heating, and cooling), but it is reliable. While solar and wind energy are intermittent, heat is consistently radiated from deep underground. Additionally, the cool temperatures closer to the surface needed for geothermal heat pumps are present year round and at all locations. Geothermal power plants for electricity generation, however, can only be built in specific locations where hot magma is close enough to the Earth's surface. These locations are typically associated with geysers, hot springs, or volcanoes (figure $18.4.e$). Additionally, geothermal power plants are costly to build.

Figure $18.4.e$: Locations of the world's volcanoes. They are concentrated along the west coasts of North American and South America as well as just east of Asia and Australia. These regions, which wrap around the Pacific Ocean, form what is known as the Ring of Fire. Image by Salazar, S.S., Muñoz, Y. & Ospino, A. Analysis of geothermal energy as an alternative source for electricity in Colombia. *Geotherm Energy* **5,** 27 (2017). (CC-BY)

The environmental impact of geothermal energy depends on how it is being used. The use of geothermal heat pumps has almost no negative impact on the environment. Geothermal power plants do not burn fuel to generate electricity, so they generate minimal air pollution. They release less than 1% of the carbon dioxide emissions of a fossil fuel plant. Geothermal plants plants use scrubber systems to clean the air of hydrogen sulfide that is naturally found in the steam and hot water. They emit 97% less sulfur compounds (one cause of acid deposition/acid rain) than are emitted by fossil fuel plants. After the steam and water from a geothermal reservoir have been used, they are injected back into the Earth. One environmental concern associated with geothermal power plants is geothermal drilling during their construction has caused earthquakes, similar to the effects of injection wells for fracking.

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18.5: Hydropower

Hydropower (hydroelectric energy) refers to the energy in moving water, which can be used to generate electricity. It is ultimately driven by solar energy. Water at high elevations is replenished through evaporation (induced by solar heat), condensation, and precipitation. The moving water turns a turbine (figure $18.5.a$) and this moves magnets within a wire coil, causing the movement of electrons in a generator. The result is an electric current (electricity). Combustion of fossil fuels or biofuels, nuclear energy, wind energy, and thermal solar systems all follow this same general mechanism; the difference is what causes the turbine to spin.

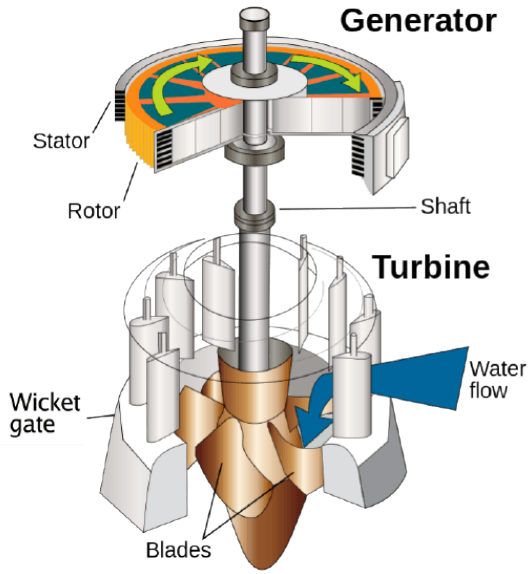

Figure $18.5.a$: A water turbine. Moving water turns the blades of the turbine. The wicket gate controls the water flow. The moving water causes magnets in the rotor to spin and move electrons within the loops of wire in the stator, generating an electric current. Image by U.S. Army Corps of Engineers (public domain).

There are several types of hydropower, but each generates electricity through the same general mechanism described above. The most well-known use of hydropower involves dams. **Dams** block the flow of rivers, producing an artificial lake (reservoir) upstream. The release of water is then controlled. Some of this water moves through a channel (penstock), and this kinetic energy (energy of motion) is harnessed into electricity (figure $18.5.b$). In **run-of-the-river hydroelectricity**, the turbine is placed directly into a river, and the natural flow of water through the river spins the turbine. **Tidal energy** and **energy from ocean waves** (figure $18.5.c$) are also considered forms of hydropower. However, tidal energy arises from the gravitational attraction of the moon and the more distant sun on the earth's oceans, combined with rotation of the earth. In other words, most forms of hydropower are indirect forms of solar energy, with the exception of tidal energy.

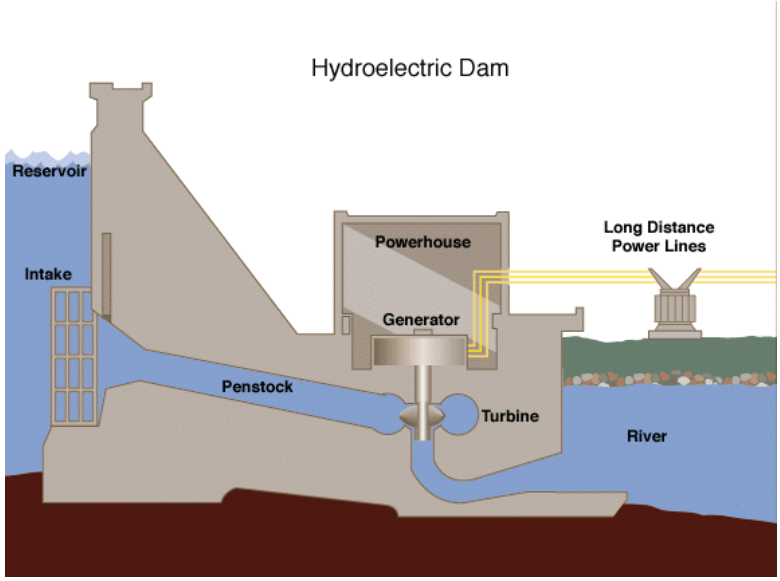

Figure $18.5.b$: A section of a hydroelectric dam. Water in the reservoir passes through the intake into the penstock, which is a narrow channel. The moving water turns a turbine. This powers the generator in the powerhouse. The water continues down the river. Meanwhile electricity is distributed through long distance power lines. Image by Tennessee Valley Authority (public domain).

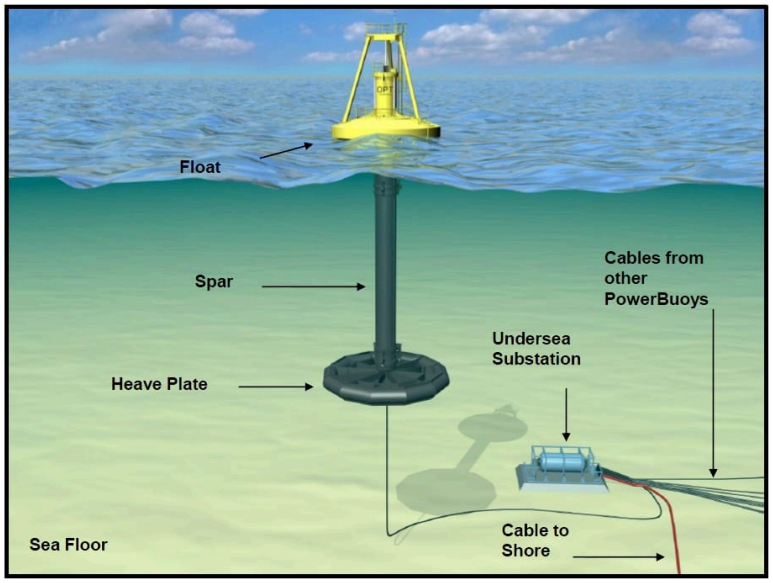

Figure $18.5.c$: One way to harness wave energy is with an absorber. Abosorbers extract energy from the rise and fall of the waves with a buoy. The buoy consists of the float, which is above the water and a heavy plate. The narrow spar connects the two. A cable connects the heavy plate of each buoy to an undersea substation, and another cable runs from the substation to the shore. Image and caption (modified) by OpenEI (public domain).

Small hydropower projects offer power solutions for many remote communities throughout the world, such as those in Nepal, India, China, and Peru, as well as for highly industrialized countries like the United States. **Small hydropower systems** are those that have a capacity between 0.01 to 30 megawatt (MW) of power. For reference, a 1-MW generator operating for an hour (producing 1 MWh) generates enough electricity to powers the average home in the U.S. for a little over a month. Small hydropower systems that generate less than 0.1 MW are more specifically called **microhydropower** systems (figure $18.5.d$). Most of the systems used by home and small business owners would qualify as microhydropower systems. In fact, a 10 kW system generally can provide enough power for a large home, a small resort, or a hobby farm.

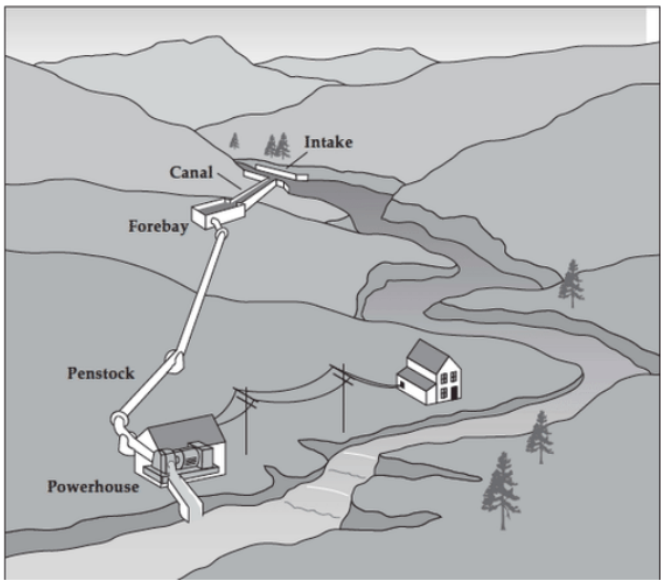

Figure $18.5.d$: A microhydropower system. Although there are several ways to harness the moving water to produce energy, run-of-the-river systems, which do not require large storage reservoirs, are often used for microhydropower projects. For run-of-the-river hydro projects, a portion of a river's water is diverted to a channel, pipeline, or pressurized pipeline (penstock) that delivers it to a waterwheel or turbine. In this image, water from the river moves through the intake then to the canal, forebay, penstock, and powerhouse, which contains the turbine. The moving water rotates the wheel or turbine, which spins a shaft. The motion of the shaft can be used for mechanical processes, such as pumping water, or it can be used to produce electricity. In this image, electrical lines connect the powerhouse to a nearby house.

One benefit of using hydropower is that dams and reservoirs can additionally be used for recreation, flood control, and storing freshwater (see Water Scarcity and Solutions). While we will never run out of moving water, the potential to use hydropower fluctuates based on precipitation. For example, during a drought, water levels in a reservoir decreases, and there is less water released to generate electricity. As with most sources of renewable energy, hydropower is not practical everywhere, and it is most effective in mountainous regions with high rainfall and snowmelt.

Hydropower dams and the reservoirs they create degrades habitat and negatively impacts native species. For example, migration of fish to their upstream spawning areas can be obstructed by dams. In areas where salmon must travel upstream to spawn, such as along the Columbia River in Washington and Oregon, the dams block their way (figure $18.5.e$). This problem can be partially alleviated by using "fish ladders" that help salmon get around the dams (figure $18.5.f$). Fish traveling downstream, however, can get killed or injured as water moves through turbines in the dam. Reservoirs and operation of dams can also affect aquatic habitats due to changes in water temperatures, water depth, chemistry, flow characteristics, and sediment loads, all of which can lead to significant changes in the ecology and physical characteristics of the river both upstream and downstream. When reservoirs first fill with water, they inundate terrestrial (land) habitats, farms, cities, and archeological and cultural sites, sometimes forcing populations to relocate. The terrestrial vegetation slowly decomposes in oxygen-poor conditions, releasing methane into the atmosphere, a potent greenhouse gas. In this sense, hydropower generates few air pollutants during operation, but construction does contribute to climate change.

Figure $18.5.e$: The Grand Coulee Dam on the Columbia River in Washington state created Lake Roosevelt, which provides outdoor recreation such as fishing and swimming. However, it compromised salmon populations and flooded sacred sites for people of the Spokane Tribe. Image by U.S. Bureau of Reclamation (public domain).

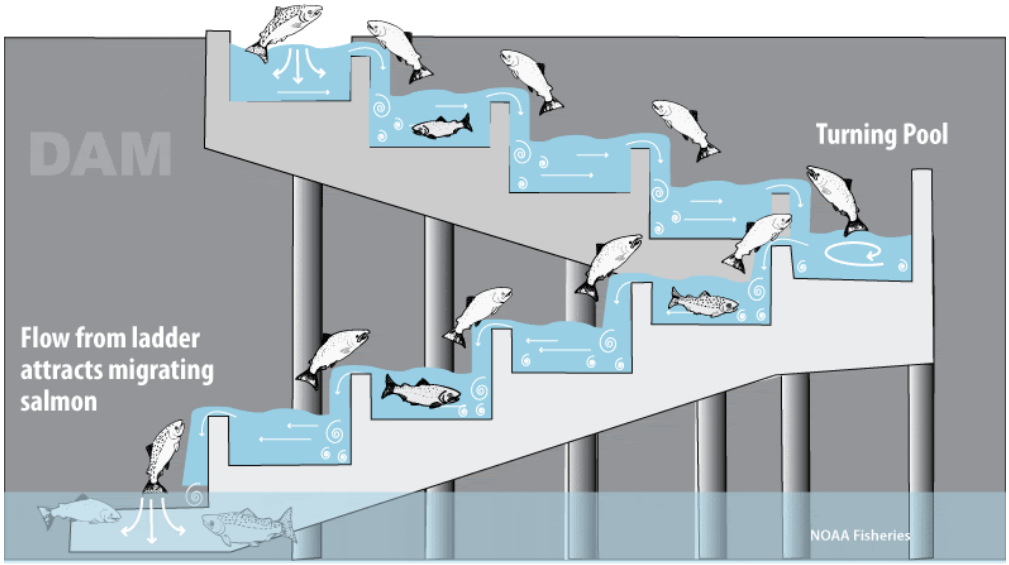

Figure 18.5.f: Left: The fish ladder at John Day Lock and Dam along the Columbia River in Oregon allows adult fish to migrate upstream of the dam on their own. Right: Diagram of a fish ladder, which allows the passage of salmon over a dam. Salmon swim upstream to spawn (reproduce) and are able to swim up the steps of the ladder. The flow from the ladder attracts migrating salmon. At the turning pool, they rotate and then proceed up the next flight of the ladder until they are over the dam. Left image and caption (modified) from U.S. Army Corps of Engineers, and right image by NOAA Fisheries (public domain).

While large-scale dam hydropower projects are often criticized for their impacts on wildlife habitat, fish migration, and water flow and quality, small run-of- the-river projects are free from many of these environmental problems. Because they use the natural flow of the river, they hardly alter the stream channel and flow. Thus, effects such as oxygen depletion, increased temperature, decreased flow, and impeded upstream migration are not problems for many run-of-the-river projects.

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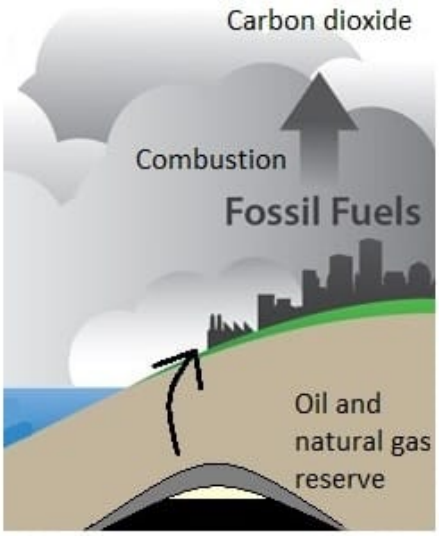
18.6: Biofuels (Biomass Energy)

Biofuels (biomass energy) contain energy produced from organisms, such as animal waste, plants, or algae. It is another indirect form of solar energy. Biofuels have many uses. They be burned directly or first converted to ethanol (often with the help of bacteria and fungi) to generate electricity. The heat from combustion produces steam and turns a turbine to power a generator. Biodiesel offers an alternative to petrochemicals for fueling vehicles. Biofuels have even been used to power small planes (figure $18.6.a$). Furthermore, burning wood or straw provides heating.

Figure $18.6.a$: Test flight of the "Green Hornet", a Navy fighter jet partially powered by biofuels. Image by U.S. Navy (public domain).

Unlike fossil fuels, biofuels are **carbon neutral** (figure $18.6.b$). Fossil fuels store carbon that was captured by organisms millions of years ago. When we burn them, carbon dioxide is released much more rapidly than it was removed. Biofuels removed carbon dioxide from the atmosphere more recently, and they form over shorter time spans. When biofuels are burned, this carbon dioxide that was recently removed is released back into the atmosphere.



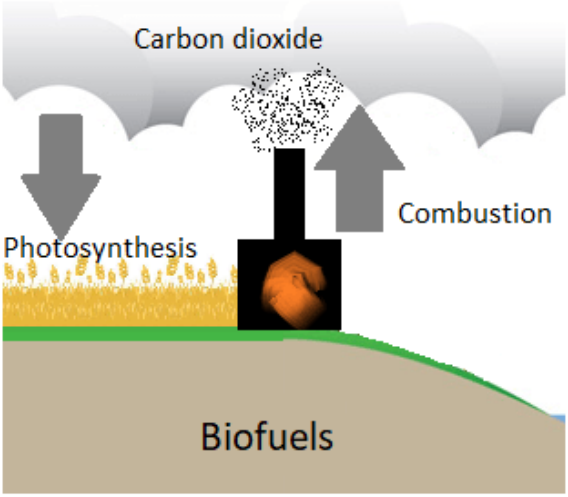


Figure 18.6.b: Fossil fuels, such as oil and natural gas, contain carbon that has been stored underground for millions of years. Combustion (burning) of these fossil fuels releases carbon dioxide into the atmosphere, contributing to climate change. When biofuels are grown, they capture carbon dioxide through photosynthesis. Burning them or their products for heat, transportation, or electricity generation release this carbon dioxide, which was only recently captured. For this reason, biofuels are considered carbon neutral. Images created by Melissa Ha from NETL/DOE (public domain) and publicdomainvectors.org (public domain).

Another advantage of biofuels is that they can be produced locally and can be cultivated in many different locations. On the other hand, they occupy space that could otherwise be used for food production. To further complicate matters, the characteristics that make a plant species ideal for biofuel (such as being resistant to pests and fast-growing) are also characteristics that help invasive species thrive. Care must taken to contain these species if grown outside of their native ranges.

Combustion of solid municipal waste (see below) or animal wastes as biofuels, reduces waste and generates electricity simultaneously. Unlike most forms of renewable energy, however, combustion of biofuels pollutes the air. (The carbon dioxide released is not an issue since biofuels are carbon neutral, but other air pollutants are also released.) In fact, indoor air pollution from fires used for cooking inside the home is a major cause of death in developing countries.

Each type of biomass must be evaluated for its environmental and social impact in order to determine if it is really advancing sustainability and reducing environmental impacts. For example, cutting down large swaths of forests just for energy production is not a sustainable option because our energy demands are so great that we would quickly deforest the world, destroying critical habitat. For biomass to be a sustainable option, it usually needs to come from waste material, such as lumber mill sawdust, paper mill sludge, yard waste, or oat hulls from an oatmeal processing plant, livestock manure, or trash. These materials would

otherwise just accumulate or decompose. Several examples of biofuel use are discussed below in more detail, including the specific advantages and disadvantages of type of use.

Burning Wood

Using wood, and charcoal made from wood, for heating and cooking can replace fossil fuels and may result in lower carbon dioxide emissions. If wood is harvested from forests or woodlots that have to be thinned or from urban trees that fall down or needed be cut down anyway, then using it for biomass does not impact those ecosystems. However, wood smoke contains harmful pollutants like carbon monoxide and particulate matter (see Air Pollution).

For home heating, it is most efficient and least polluting when using a modern wood stove or fireplace insert that are designed to release small amounts of particulates. However, in places where wood and charcoal are major cooking and heating fuels such as in developing countries, the wood may be harvested faster than trees can grow resulting in deforestation (figure $18.6.c$). The largest share of biofuel use comes from traditional biomass, mostly fuel wood gathered for household cooking and heating, often without regard for sustainable replacement.

Figure $18.6.c$: Charcoal production in Uganda. (A) Trees cut down for charcoal. (B) Pieces of firewood. (C) Wood logs read for charcoal burning. (D) Charcoal packed and ready for market. Image and caption (modified) from Bamwesigye et al. *Sustainability* **2020**, 12(20), 8337. (CC-BY)

Biomass can be used in small power plants. For instance, Colgate College has had a wood-burning boiler since the mid-1980s (figure $18.6.d$). In one year it processed approximately 20,000 tons of locally and sustainably harvested wood chips, the equivalent of 1.17 million gallons (4.43 million liters) of fuel oil, avoiding 13,757 tons of emissions and saving the university over $1.8 million in heating costs. The University's steam-generating wood-burning facility now satisfies more than 75% of the campus's heat and domestic hot water needs.

Figure 18.6.d: Wood chips are one example of a biofuel that can be burned to generate electricity. Source: Ulrichulrich

Municipal Solid Waste

Municipal solid waste (MSW) is commonly known as garbage and can create electricity by burning it directly or by burning the methane produced as it decays. Waste-to-energy processes are gaining renewed interest as they can solve two problems at once: disposal of waste and production of energy from a renewable resource. Many of the environmental impacts are similar to those of a coal plant: air pollution, ash generation, etc. Because the fuel source is less standardized than coal and hazardous materials may be present in MSW, incinerators and waste-to-energy power plants need to clean the gases of harmful materials. The Environmental Protection Agency in the U.S. regulates these plants very strictly and requires anti-pollution devices to be installed. Also, while incinerating at high temperature, many of the toxic chemicals may break down into less harmful compounds. The ash from these plants may contain high concentrations of various metals that were present in the original waste. If ash is clean enough it can be “recycled” as an MSW landfill cover or to build roads, cement blocks, and artificial reefs (similar to coral reefs, but built by humans).

Landfill Gas (Biogas)

Landfill gas (**biogas**) is a sort of human-made “biogenic” gas as discussed above (figure 18.6.e). Methane is formed as a result of biological processes in sewage treatment plants, waste landfills, anaerobic composting, and livestock manure management systems. This gas is captured and burned to produce heat or electricity. The electricity may replace electricity produced by burning fossil fuels, reducing carbon dioxide emissions. The only environmental impacts are from the construction of the plant itself, similar to that of a natural gas plant.

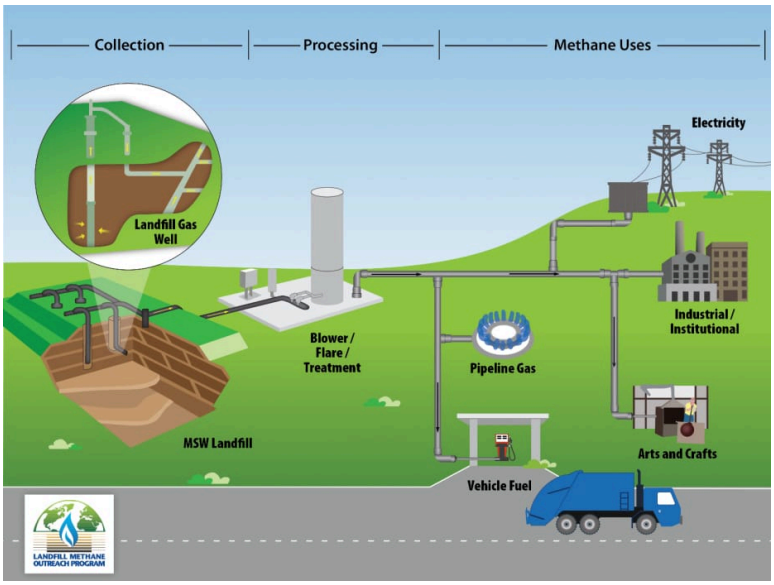


Figure $18.6.e$: The collection and processing of landfill gas to produce methane for multiple uses. First, landfill gas is collected from the landfill gas well. A system of vertical and horizontal piping buried in an municipal solid waste landfill. The landfill gas is then processed and treated for use (blower/flare/treatment). Potential end uses include industrial/institutional uses, arts and crafts, pipeline gas, and vehicle fuel. Image and caption (modified) from Landfill Methane Outreach Program/EPA (public domain).

Bioethanol and Biodiesel

Bioethanol and **biodiesel** are liquid biofuels manufactured from plants, typically crops. Bioethanol can be easily fermented from sugar cane juice, as is done in Brazil. Additionally, it can be fermented from broken down corn starch, as is mainly done in the United States.

The economic and social effects of growing plants for fuels need to be considered, since the land, fertilizers, and energy used to grow biofuel crops could be used to grow food crops instead. The competition of land for fuel versus food can increase the price of food, which has a negative effect on society. It could also decrease the food supply increasing malnutrition and starvation globally. Also, in some parts of the world, large areas of natural vegetation and forests have been cut down to grow sugar cane for bioethanol and soybeans and palm-oil trees to make biodiesel. This is not sustainable land use. Derived biofuels from parts of plants not used for food, such as stalks, reduces their environmental impact. Biodiesel can be made from used vegetable oil and has been produced on a very local basis. Compared to diesel, a petrochemical derived from crude oil, biodiesel combustion produces less sulfur oxides, particulate matter, carbon monoxide, and unburned and other hydrocarbons, but it produces more nitrogen oxide (see Air Pollution).

Liquid biofuels typically replace petroleum and are used to power vehicles (figure $18.6.f$). Although ethanol-gasoline mixtures burn cleaner than pure gasoline, they also are more volatile and thus have higher “evaporative emissions” from fuel tanks and dispensing equipment. These emissions contribute to the formation of harmful, ground level ozone and smog (see Air Pollution). Gasoline requires extra processing to reduce evaporative emissions before it is blended with ethanol.

Figure $18.6.f$: A bus running on soybean biodiesel. Image and caption (modified) from U.S Department of Energy (public domain).

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18.7: Energy Conservation

Energy conservation refers to reducing energy waste and increasing efficiency. Energy conservation can involve behavior changes as well as technologies. Some examples of energy conservation have no financial impact. These include turn off and unplugging electronics when not in use, turning down the water heater, and driving efficiently (figure $18.7.a$). Additionally, opening blinds on south-facing windows in the morning during the winter takes advantage of a passive solar technology. Relying on the sun for heating and lighting reduces the use of electricity.

Figure $18.7.a$: A plant on the dashboard of this Ford Fusion (right) indicates if the driver's behavior promotes fuel efficiency. In this picture, there is only one leaf on the plant, indicating low efficiency. Some ways to drive efficiently include following the speed limit and adjusting your speed gradually. Image by ogilvyprworldwide (CC-BY).

Other examples of energy conservation require some financial investment, but they quickly pay for themselves with savings on an energy bill. An **energy audit** is a first step to investigate inefficiencies in one's home. This helps homeowners identify where their home is losing energy, and which problem areas and fixes they should prioritize to save energy and money. For example, an energy audit may reveal places in the home where hot escaping in the winter or entering in the summer. An energy auditor might recommend installing insulation to better seal the home as well as to insulate the hot water heater and pipes. Investing in most high-efficiency appliances also pays for itself relatively quickly (figure $18.7.b$).

Figure 18.7.b: Energy Star appliances use energy efficiently. Image by MoneyBlogNewz (CC-BY)

This video provides a walkthrough of an energy audit.

YouTube Video

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

View this YouTube Video online

Finally, some strategies for energy conservation require sizeable financial investment. They can eventually pay for themselves over extended periods of time. Once example are double-paned, low emissivity (low e) windows (figure 18.7.c). The two layers of glass trap air between them, which serves as insulation. Additionally, the glass is coated with very small metal dots that allow light to pass through, but infrared (heat) energy is reflected back. If it is hotter outside, heat is emitted back outside; if warmer inside, heat will be emitted back inside. Energy-efficient air conditioners, geothermal heat pumps, and on-demand (tankless) water heaters (figure 18.7.d) are also examples of energy-conserving technologies that require sizeable investment.

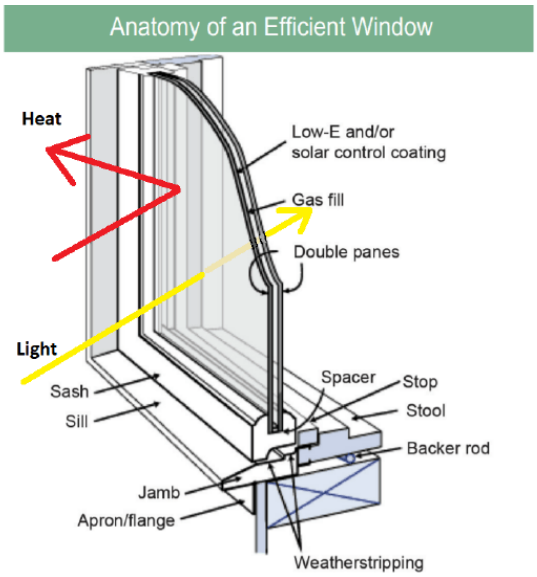

Figure 18.7.c: Anatomy of an efficient window. A double-paned, low emissivity window allows light from the sun to pass through, but tiny metal dots (not visible) reflect heat (labeled "Low-E and/or solar control coating"). The double panes trap air between them, an insulator (labeled "gas fill"). Spacers are between the glass and the sash, which surrounds the glass. The sash can move out of the frame when the window is open, and weatherstipping prevents air from leaking between the sash and the frame. The stop on the outside prevents the sash swinging outward, and the stool extends perpendicular to the wall outside of the stop. Under it is a backer rod, filling the space between the stool and the wall beneath it. The frame consists of the horizontal sill and vertical jamb. The apron/flange is the trim just below the frame. Image modified from U.S. Department of Energy (public domain).

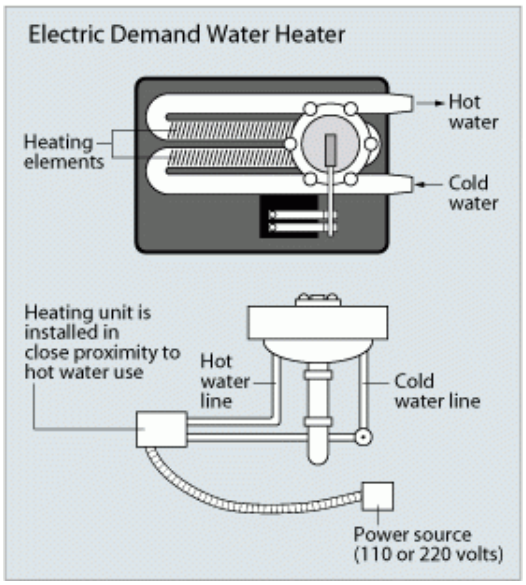

Figure 18.7.d: An tankless water heater (electric demand water heater). Because hot water is not stored, there is no opportunity for it to cool and need to be reheated. This conserves energy. The heating unit is installed in close proximity to hot water use. It is suppled by a power source (110 or 220 volts). Hot and cold water lines run from the heating unit (which contains heating elements) to the sink. Image by U.S. Department of Energy (public domain).

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18.8: Data Dive- Global Renewable Energy Generation

Overview

Our World in Data (OWID) is a scientific online publication that focuses on using research and data to help tackle global concerns such as poverty, disease, hunger, climate change, war, and inequitable treatment of our world's most vulnerable and unstable communities. Their website is particularly known for publishing a variety of graphs, some even interactive, to present the research that helps explain causes and consequences of global concerns to the public. One example graph, seen below, illustrates renewable energy generation:

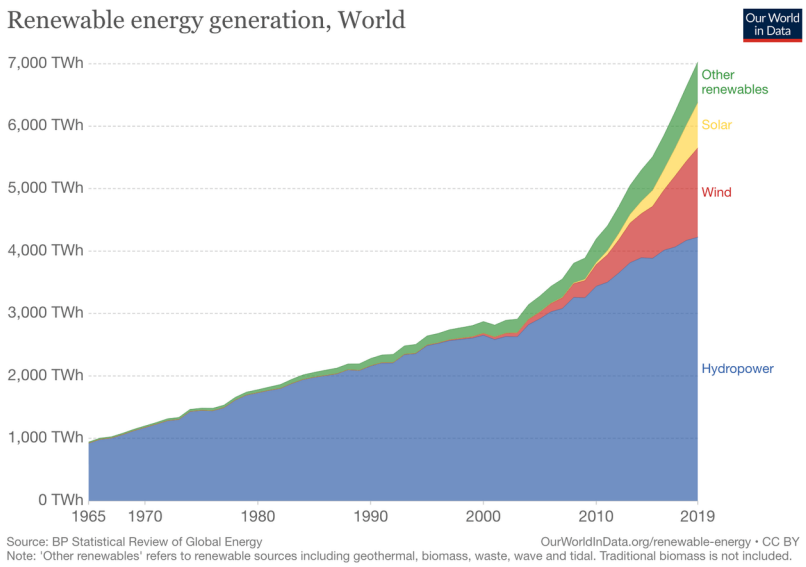

Figure $18.8.a$: Global renewable energy generation. Graph by Our World in Data (CC-BY).

Questions

1. What renewable energy source has had the most consistent use globally?
2. Based on what you have learned in the chapter, what sources do you think are in the "other" category? Don't peek on the website!
3. Describe the pattern you see for the "other" category for 1965 to 2019.
4. Moving into the future, which renewable energy source do you think will grow the most in the next 50 years? Why?

Raw Data For Above Graph(s)

Raw data table link for Our World In Data graph above. (CC-BY)

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18.9: Review

Summary

After completing this chapter you should be able to...

- Detail the percentage that renewable energy contributes to electricity generation and total energy consumption globally and in the United States.
- Distinguish among the five main types of renewable energy, explain the mechanisms by which they are used, and discuss their advantages and disadvantages.
- Distinguish between passive and active solar technologies and provide examples of each.
- Explain how solar panels generate electricity.
- Distinguish between geothermal power plants and geothermal (ground source) heat pumps.
- Identify the main types of hydropower.
- Explain how environmental damage associated with hydropower can be mitigated.
- Explain why combustion of biofuels is carbon neutral.
- Provide examples of biofuel use and evaluate their sustainability.
- Define energy conservation and provide examples of behaviors and technologies that conserve energy.

Renewable energy sources can be replenished within a short timeframe. This includes **wind**, **solar**, **geothermal**, **hydropower**, and **biofuels**. Each is a direct or indirect form of solar energy with the exception of geothermal energy, which comes from deep underground, and tidal energy, a type of hydropower. Most forms of renewable energy generate electricity by turning a turbine, which powers a generator. For wind energy and hydropower, the motion of air or water, respectively, turns the turbine. For geothermal energy and biofuels, heat from the Earth or from burning organisms, respectively, produce steam, which turns a turbine. Solar panels generate electricity when light energy displaces electrons in semiconductors.

Generally, renewable energy sources generate little air pollution and are not major causes of climate change, but there are exceptions. A downside of renewables is that wind and solar can only be efficiently harnessed in certain locations and are intermittently available. Geothermal energy is more reliable, but geothermal power plants can typically only be built near geysers, volcanoes, or hot springs. Hydropower that involves **dams** and **reservoirs** destroys terrestrial habitats and disrupts aquatic species, but **run-of-the-river hydroelectricity** causes minimal damage. Biofuels are **carbon neutral**, capturing as much carbon dioxide as they release. Biofuels are most sustainable when they are made from materials that would otherwise be wasted.

Energy conservation involves reducing energy use or using it more efficiently. Examples of energy conservation include turning off lights and electronics when they are not in use, driving efficiently, and purchasing energy-efficient applicances.

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UNIT 6: ENVIRONMENTAL IMPACTS

The human presence and impact on this Earth has been changing with our population, technology, and affluence. In order to start understanding how these variables have an impact on Earth (in a general sense) the **IPAT** equation was created. 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
- "T" is 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. To achieve meaningful reductions of human impact, there are intense debates on where the focus should lie. Where one group sees expensive remedies with little demonstrable return, another sees opportunities for investment in new technologies, businesses, and employment sectors, with collateral improvements in global and national well-being.

This unit will investigate variables that represent the biggest modern components for human impact at local and global scales. Specifically, it will focus on solid waste, pollution, and climate change.

19: Solid Waste Management

19.1: Waste Generation

19.2: Waste Disposal

19.3: Solid Waste and Marine Life

19.4: Waste Reduction

19.5: Data Dive- "Flushable" Wipes

19.6: Review

20: Pollution

20.1: Water Pollution

20.1.1: Water Pollutants and Their Sources

20.1.2: Water Treatment

20.1.3: Mitigating Water Pollution

20.2: Air Pollution

20.2.1: Ozone Depletion

20.2.2: Acid Deposition

20.3: Data Dive- Plastic in World Oceans

20.4: Review

21: Climate Change

21.1: The Greenhouse Effect and Climate Change

21.2: Data Dive- Flooding in Venice Italy

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19: SOLID WASTE MANAGEMENT

Chapter Hook

Flushable wipes, are flushable right? No. Over and over, plumbers and waste water treatment workers state that they do not degrade fast enough and clogs drains and sewers across the globe. Not all flushable wipes are created equal, and some are better than others. Unfortunately, there are no legal requirements these products are required to passed to be called flushable, and the only guiding body is the integrity of the company manufacturing the wipes. If you want advice about your body you go to your doctor. If you want advice about your pipes, talk to your plumber. They will tell you that the only things that should go down your toilet are the 3 P's, pee, poo, and (toilet) paper.

Figure \(\PageIndex{a}\): Wipe isle at the store. Image by 維基小霸王 in Wikimedia Commons (CC-BY-SA4.0)

19.1: Waste Generation

19.2: Waste Disposal

19.3: Solid Waste and Marine Life

19.4: Waste Reduction

19.5: Data Dive- "Flushable" Wipes

19.6: Review

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19.1: Waste Generation

In natural systems, there is no such thing as waste. Everything flows in a natural cycle of use and reuse. Living organisms consume materials and eventually return them to the environment, usually in a different form, for reuse. **Solid waste** (or trash) is a human concept. It refers to a variety of discarded materials, not liquid or gas, that are deemed useless or worthless (figure $19.1.a$). Humans modify natural substances, making them more difficult to breakdown, or store matter under conditions that slow its degradation. However, what is worthless to one person may be of value to someone else, and solid wastes can be considered misplaced resources. Learning effective ways to reduce the amount of wastes produced and to recycle valuable resources contained in the wastes is important if humans wish to maintain a livable and sustainable environment.

Figure $19.1.a$: Trash is a uniquely human concept. Image by Piqsels (public domain).

Types of Waste

There are many subcategories of waste (figure $19.1.b$). **Biodegradable** waste can be broken down by microbes whereas **nondegradable** waste does not readily break down. **Hazardous waste** is trash that presents a health risk. Specifically, hazardous wastes are defined as materials which are toxic, **carcinogenic** (cause cancer), **mutagenic** (cause DNA mutations), **teratogenic** (cause birth defects), highly flammable, corrosive, or explosive. Examples include batteries, fluorescent lights, various cleaners, and **e-waste**, which arises from discarded electronics. Precious metals can be extracted and recycled from hazardous waste, but it must be done safely.

Figure $19.1.b$: Plastic cutlery is nondegradable, but these spoons and forks and made of wood, a biodegradable material. Image by BRRT/ Pixabay (Pixabay license).

Interactive Element

How do you dispose of household hazardous wastes? Check Earth 911 for disposal sites near you.

Solid Waste Sources and Composition

Agriculture and industry generate most of the waste globally followed by mining (figure $19.1.c$). Together, these generate **non-municipal solid waste**. Some common items that are classified as non-municipal waste are: construction materials (roofing shingles, electrical fixtures, bricks); waste-water sludge; incinerator residues; ash; scrubber sludge; oil/gas/mining waste; railroad ties, and pesticide containers. The remaining waste, **municipal solid waste** (MSW), is made up of discarded solid materials from residences, businesses, and city buildings. Globally, waste generated from industry generated was nearly 18 times that of MSW, and waste generated from agriculture was more than 4.5 times that of MSW.

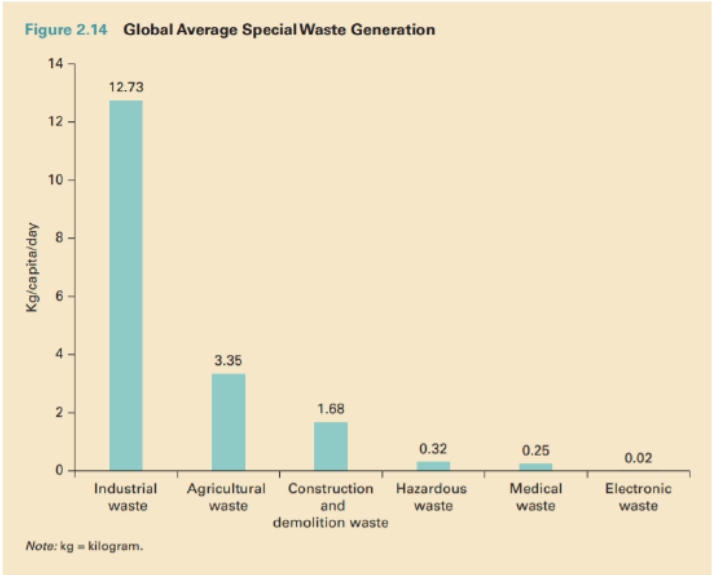

Figure $19.1.c$: Global average special waste generation showing selected categories of waste in kilograms (kg) per person (capita) per day. 1 kg = 2.2 lbs. In order of greatest to least waste generation is industrial waste (12.73 kg/capita/day), agricultural waste (3.35), construction and demolition waste (1.68), hazardous waste (0.32), medical waste (0.25), and electronic waste (0.02). Image from What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050 (CC-BY)

The world generates 2.21 billion tons of municipal solid waste annually. Municipal solid waste makes up 3-9% of all waste in the U.S., and 292.4 million tons were generated in U.S. in 2018 (4.9 lbs per person per day). This contrasts with average values in Sub-Saharan Africa (1.01 lbs per person per day), South Asia (1.15 lbs per person per day), and East Asia and the Pacific (1.23 lbs per person per day). Daily waste generation per person in high income countries is projected to increase by 19 percent by 2050, compared to low- and middle-income countries where it is anticipated to increase by approximately 40 percent or more.

Municipal solid waste consists of materials from plastics to food scraps. The most common waste product is paper (about 23% of the total; figure $19.1.d$). Other common components are yard waste (green waste), plastics, metals, wood, glass and food waste. The composition of the municipal wastes can vary from region to region and from season to season.

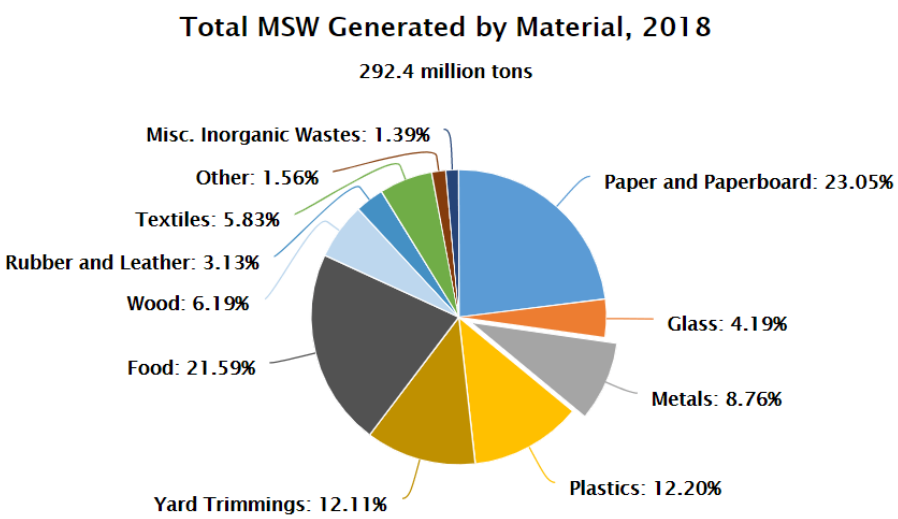

Figure $19.1.d$: Composition of municipal solid waste (MSW) in the U.S. in 2018 before recycling. Paper and paperboard comprise 23.05% followed by food (21.59%), plastics (12.20%), yard trimmings (12.11%), metals (8.76%), wood (6.19%), textiles (5.83%), glass (4.19%), rubber and leather (3.13%), other (1.56%), and miscellaneous inorganic waste (1.39%). Image from EPA (public domain).

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- Kaza, Silpa; Yao, Lisa C.; Bhada-Tata, Perinaz; Van Woerden, Frank. 2018. What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050. Urban Development;. Washington, DC: World Bank. © World Bank. (CC-BY)

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19.2: Waste Disposal

There are three primary methods for waste disposal: open dumps, sanitary landfills, and incineration. Sanitary landfills and incineration prevent reuse, recycling, and proper decomposition. While open dumps promote decomposition better than other methods of waste disposal and allow discarded materials to be salvaged or recycled, they promote disease spread and cause water pollution. They are thus illegal in many countries.

Open Dumps

Open dumps involve simply piling up trash in a designated area and is thus the easiest method of waste disposal (figure $19.2.a$). Open dumps can support populations of organisms that house and transmit disease (reservoirs and vectors, respectively). Additionally, contaminants from the trash mix with rain water forming **leachate**, which infiltrates into the ground or runs off. This liquid leachate may contain toxic chemicals such as dioxin (a persistent organic pollutant), mercury, and pesticides.

Figure $19.2.a$: An open dump in Vietnam. Image by Julien Belli (CC-BY).

Sanitary Landfills

After recycling, composting, and incineration, the remaining 50% of municipal solid waste (MSW) in the U.S. was discarded in **sanitary landfills** (figure $19.2.b$). Trash is sealed from the top and the bottom to reduce contamination of surroundings (figure $19.2.c$). Rainwater that percolates through a sanitary landfill is collected in the bottom liner, and this bottom layer thus prevents contamination of groundwater. The groundwater near the landfill is closely monitored for signs of contamination from the leachate. Layers of soil on top prevent disease spread. Each day after garbage is dumped in the landfill, it is covered with clay or plastic to prevent redistribution by animals or the wind.

Figure $19.2.b$: A sanitary landfill in 1972. Image by Bill Shrout/EPA (public domain).

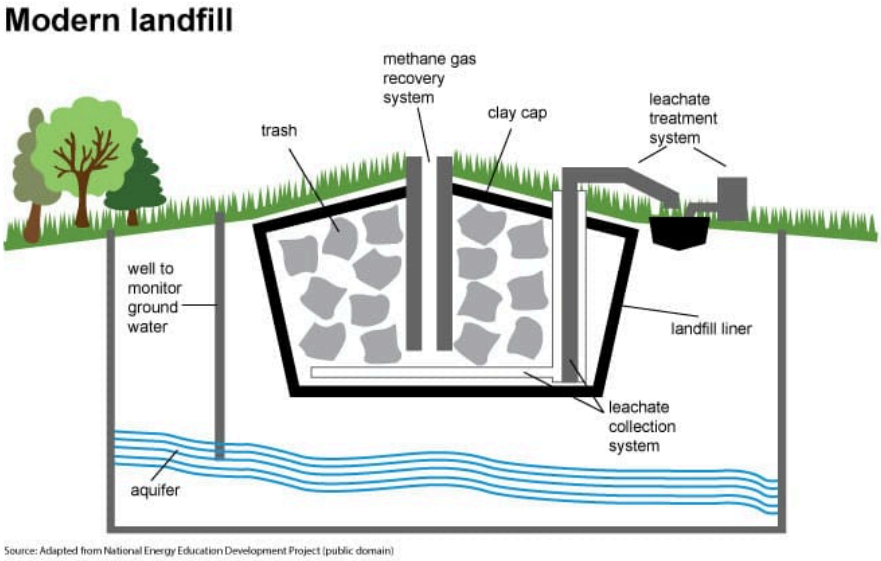

Figure $19.2.c$: A sanitary landfill. Trash is compacted and stored underground. A landfill liner prevents leachate from draining into the aquifer and contaminating groundwater, which is monitored using a well. Additionally, leachate is collected and treated (leachate treatment system). A clay cap prevents animals or wind from accessing the trash. A methane gas recovery system captures the potent greenhouse gas, which can be used as a biofuel. Image by EPA/National Energy Education Development Project (public domain).

Several practices can reduce the environmental impact of sanitary landfills. Compacting in landfills reduces water and oxygen levels, slowing decomposition and promoting methane release. In the U.S., the Clear Air Act requires that landfills of a certain size collect landfill gas (biogas), which can be used as a biofuel for heating or electricity generation. Other gases such as ammonia and hydrogen sulfide may also be released by the landfill, contributing to air pollution. These gases are also monitored and, if necessary, collected for disposal. To address the often dry condition of wastes within landfills, the concept of bioreactor landfills has emerged. These recirculate leachate and/or inject other liquids to increase moisture and promote decomposition (and therefore increasing the rate of biogas production). Upon closure, many landfills undergo "land recycling" and can be redeveloped as golf courses, recreational parks, and other beneficial uses.

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 for several reasons. Older existing landfills are increasingly reaching their authorized capacity. Additionally, stricter environmental regulations have made establishing new landfills increasingly difficult. Finally, public opposition delays or, in many cases, prevents the approval of new landfills or expansion of existing facilities.

Incineration

Incineration is simply burning trash. This has several advantages: it reduces volume and can be used to generate electricity (**waste-to-energy**). In fact, the sheer volume of the waste is reduced by about 85%. Incineration is costly, however, and it pollutes air and water. Air pollutants released by incineration include particulates, sulfur dioxide, nitrogen oxides, methane, heavy metals (such as lead and mercury), and dioxins. The byproduct of incineration, ash, is often toxic. Depending on its composition, ash might require special disposal; other types of ash can be repurposed.

An incinerator processes trash and burns it in a **combustion chamber** (figure $19.2.d-e$). The heat boils water, and the resultant steam is used to generate electricity. The smoke (called flue gases) goes through a **pollution-removal** before it is released, but it still contains some pollutants. The U.S. incinerated 11.8% of MSW in 2018.

Figure $19.2.d$: Wheelabrator Technologies' Waste-to-Energy plant in Saugus, Massachusetts has been in service since 1975. Image and caption (modified) from Fletcher6 (CC-BY).

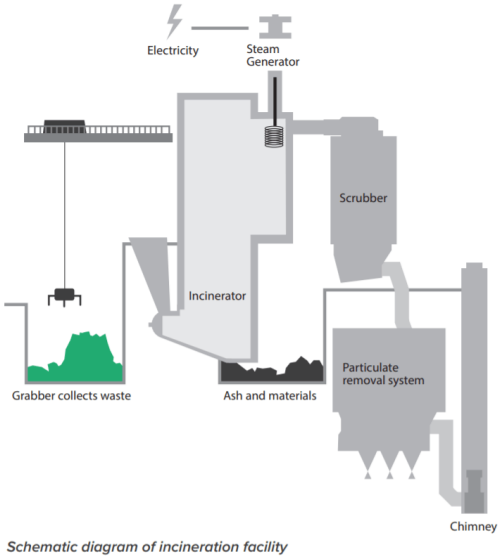

Figure $19.2.e$: A schematic diagram of a waste incineration facility (waste-to energy system). A grabber collects the waste and transfers it into the incinerator. Heat from combusting the trash is used to produce steam and generate electricity. Emissions (flue gases) pass through a scrubber and particulate removal system to limit pollution before the gases are released through a chimney. Ash remains after incineration. Image by Kaza, Silpa; Bhada-Tata, Perinaz. 2018. Decision Maker's Guides for Solid Waste Management Technologies. Urban Development Series Knowledge Papers;. World Bank, Washington, DC. © World Bank. (CC-BY)

There are two kinds of waste-to-energy systems: mass burn incinerators and refuse-derived incinerators. In **mass burn incinerators** all of the solid waste is incinerated. The heat from the incineration process is used to produce steam. This steam is used to drive electric power generators. Acid gases from the burning are removed by chemical scrubbers. Any particulates (small particles that remain suspended in the air) in the combustion gases are removed by **electrostatic precipitators**, which charge particulates and remove them with electrodes. The cleaned gases are then released into the atmosphere through a tall stack. The ashes from the combustion are sent to a landfill for disposal.

It is best if only combustible items (paper, wood products, and plastics) are burned. In a **refuse-derived incinerator**, non-combustible materials are separated from the waste. Items such as glass and metals may be recycled. The combustible wastes are then formed into fuel pellets which can be burned in standard steam boilers. This system has the advantage of removing potentially harmful materials from waste before it is burned. It also provides for some recycling of materials.

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- Biomass explained: Landfill gas and biogas. 2020. EIA. Accessed 01-18-2021 (public domain).

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19.3: Solid Waste and Marine Life

Ocean dumping has also been a popular way for coastal communities to dispose of their solid wastes. In this method, large barges carry waste out to sea and dump it into the ocean (figure $19.3.a$). That practice is now banned in the United States due to the pollution problems it created. However, much trash escapes to the ocean through littering and illegal dumping. Additionally, wind carries trash off of overfilled containers, landfills, or open dumps (where they are still used).

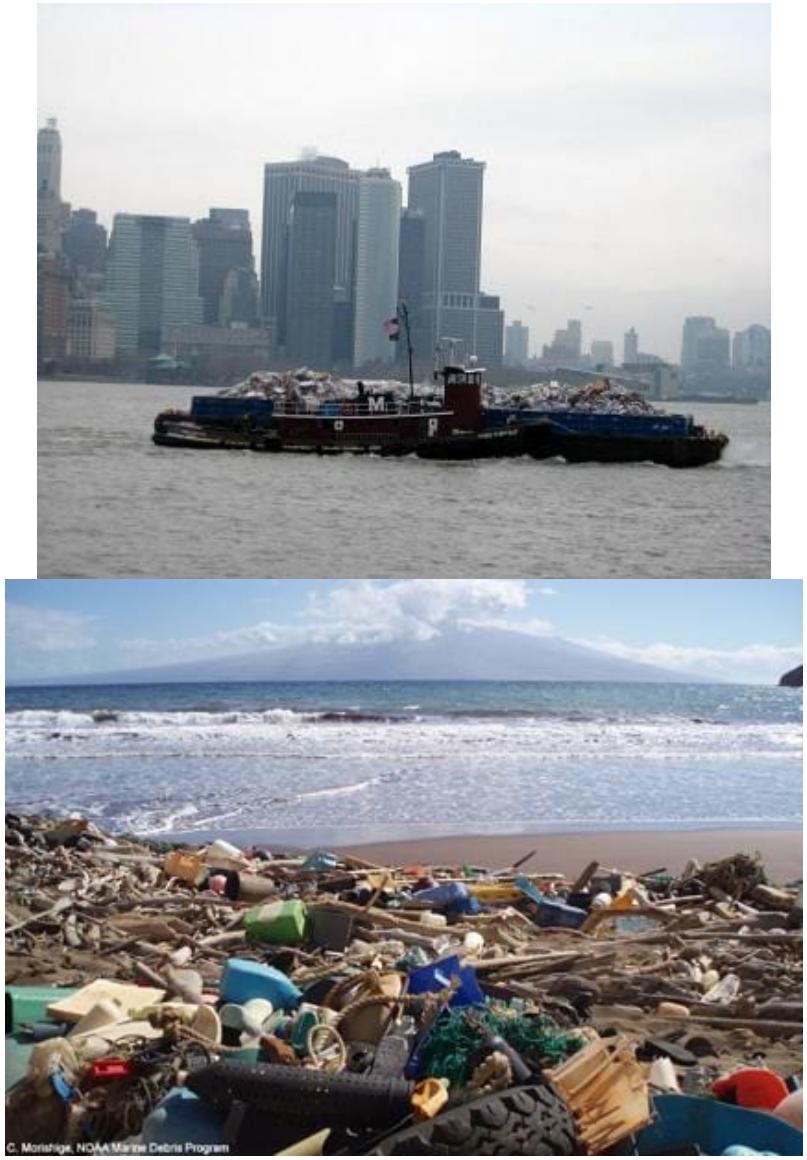

Figure $19.3.a$: Left: A garbage barge leaves Manhattan. Right: Marine debris at the beach. Left image and caption by EPA (public domain), and right image and caption by NOAA (public domain).

Garbage patches form from waste that escapes to the ocean. Plastic breaks down into smaller pieces when exposed to sunlight and ample oxygen. These pieces of plastic are trapped in calm parts of the ocean that are surrounded by strong, circular currents (figure $19.3.b$). Garbage patches may not be visible from the surface of the ocean, and the plastic pieces may be up to 20 meters deep.

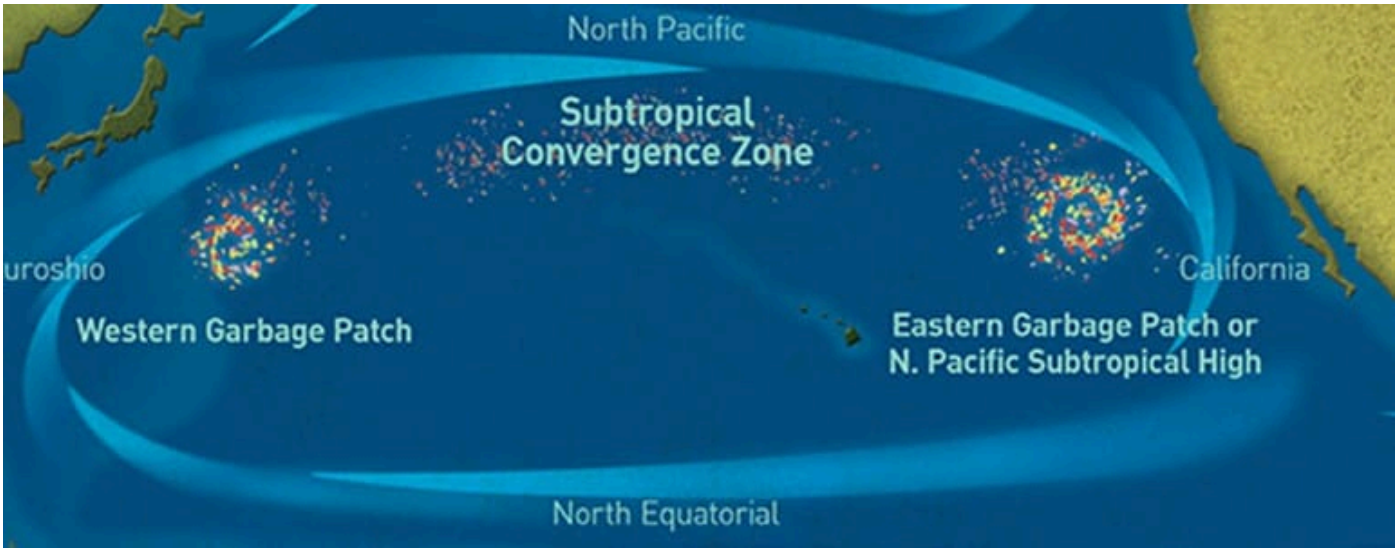

Figure $19.3.b$: Locations of the largest garbage patches in the Pacific Ocean. The Western Garbage Patch is closer to Japan, and the Eastern Garbage Patch is closer to California. The Subtropical Convergence Zone is in the middle to the north. Ocean currents including the Kuroshio Current (left), North Pacific Current (top), California Current (right), and North Equatorial Current (bottom) are labeled. Image by Boyan Slat (public domain).

Plastic and other trash harms marine life in several ways. Old fishing nets and plastic six-pack rings trap wildlife. Additionally, organisms that ingest plastic risk choking. Ingested plastic may cut internal organs, limit space available for food, and carry toxins (figure $19.3.c$).

Figure $19.3.c$: Much of this dead albatross's digestive system was filled with plastic waste. Image by Forest and Kim Starr (CC-BY).

Interactive Element

Edible six-pack rings offer a solution to the problem of plastic six-pack rings harming wildlife. You can read more about them here.

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19.4: Waste Reduction

The **waste management hierarchy** lists processes to address waste in order of preference with the goals of limiting waste, minimizing environmental impact, and maximizing additional benefits (such as electricity generation or production of recycled goods). It is symbolized as an upside triangle, meaning that the largest volume of waste should be handled using the first process (most preferred), and the smallest volume should be handled using the last process (least preferred). These processes in order of preference are reduction, recycling, energy recovery (such as incineration), treatment, and disposal (figure $19.4.a$). Individuals can exercise the first two processes by applying the four R's (see below). Unfortunately, the U.S. and the world overall, handles a large volume of waste using the least preferred method (disposal). As previously mentioned, about half of municipal solid waste (MSW) goes to a sanitary landfill for disposal. In contrast, only 23.5% of municipal solid waste (MSW) was recovered and recycled and another 8.5% was composted in 2018. Waste stream percentages also vary widely by region. As an example, San Francisco, California recycles or composts 80% of its waste material, whereas Houston, Texas recycles or composts only 19%.

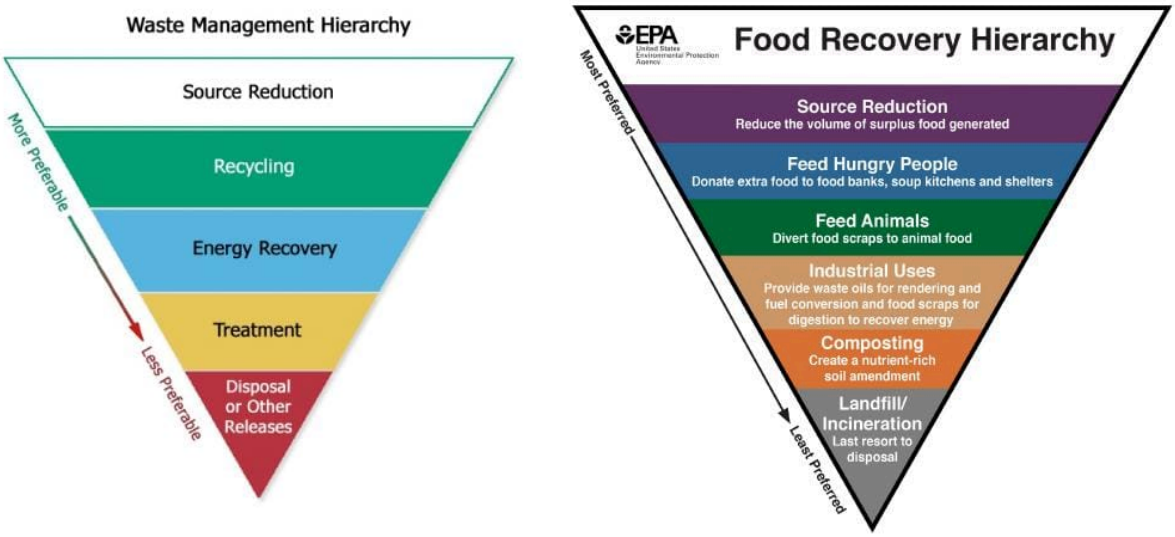

Figure $19.4.a$**:** Left: The waste management hierarchy lists processes for handling waste from most to least preferable. They are source reduction, recycling, energy recovery, treatment, and disposal or other releases. Right: The food recovery hierarchy is a waste management hierarchy specific to food waste. It begins with source reduction (reduce the volume of surplus food generated). Next is feed hungry people (donate extra food to food banks, soup kitchens, and shelters. Third is feed animals (divert food scraps to animal food. Fourth is industrial uses (provide waste oils for rendering and fuel conversion and food scraps for digestion to recover energy. Fifth is composting (create a nutrient-rich soil amendment). The remaining waste goes to landfill or incineration as a last resort to disposal. Images by EPA (public domain).

Source reduction (waste minimization) refers to the strategies that minimize the amount of generated waste and/or reduce the toxicity of the resultant waste when designing or manufacturing products or services. Waste can be reduced by reusing materials, using less hazardous substitute materials, or by modifying components of design and processing. Source reduction in manufacturing not only saves resources, but it also reduces costs for the manufacturer and indirectly for the consumer. For example, minimal packaging reduces material use, increases distribution efficiency, and reduces fuel consumption and resulting air emissions. Similarly, building materials can be designed to reduce the overall mass of material needed for a given structure.

Recycling refers to recovery and reprocessing of useful materials. Numerous examples of successful recycling and reuse efforts are encountered every day. 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 byproducts for reuse. 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 reuse. 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, and public acceptance and promotion of recycled products and applications utilizing recycled materials.

The Four R's

The **four R's** (refuse, reduce, reuse, and recycle) are strategies that allow individuals to limit the volume and negative impacts of the waste they generate. They resemble the waste management hierarchy, but focus at the individual scale rather than the scale of a company or waste management system. They are listed in order of most to least environmentally beneficial, and they are all better alternatives than discarding trash into the landfill. Recycling is last because it requires energy to reprocess waste.

To **refuse** is to decline products or processes that harm the environment if you do not need them. Choosing products without packaging is an example of refusing. To **reduce** is to choose products or processes with lower **ecological footprint** (the area of land required to produce them). Examples include products with limited packaging or durable items rather than flimsy or disposable ones. **Reuse** refers to using a product multiple times or finding an alternative use for it. For example, one could share, borrow, or rent items. A plastic yogurt or pudding container could be repurposed for storage or gardening. As noted above, **recycling** means to return used items to be reprocessed (figure $19.4.b$). Commonly recycled materials include cardboard, glass, cans, and certain plastics.

Figure $19.4.b$**:** Recycling, or returning materials to be reprocessed, is the last of the four R's. If items cannot be refused, reduced, or reused, recycling is a better alternative than discarding into the landfill. Image by Intel Free Press (CC-BY).

Resin identification codes are the triangular symbols on recyclable plastics that indicate their composition (figure $19.4.c$). A variety of materials make up plastics, and they are not all recycled the same way. Furthermore, your local recycling service may recycle some types of plastics but not others. Plastics with codes 1 and 2 are commonly recycled. For the codes, check with your local recycling service. Local businesses may house collection bins for plastics that are not commonly recycled. For example, grocery stores commonly have receptacles for recycling plastic bags, which fall under code 4.

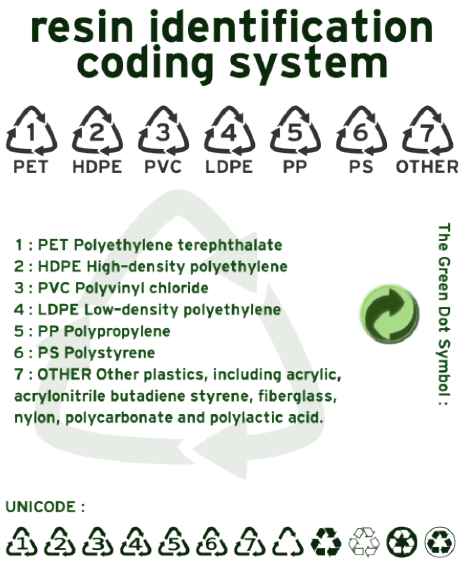

Figure $19.4.c$): The resin identification coding system explains the chemical composition of various plastics. Some are commonly recycled, and others are not. The text in the image is, "1: PET Polyethylene terephthalate, 2: HDPE High-density polyethylene, 3: PVC Polyvinyl chloride, 4: LDPE Low-density polyethylene, 5: PP Polypropylene, 6: PS Polystyrene, 7: OTHER Other plastics, including acrylic, acrylonitrille butadiene styrene, fiberglass, nylon, polycarbonate and polylactic acid. Image by Filtre/OpenClipart Library (public domain).

Interactive Element

Which items can be recycled is based on where you live and the waste management service available there. The Environmental Protection Agency provides general recycling guidelines. You local waste collector may provide an interactive website to help you determine which items to recycle. For example Recology, which serves Northern California, has a searchable website called What Bin.

Composting

Compost is organic material that can be added to soil to help plants grow (figure $19.4.d$). Food scraps and yard waste together currently make up more than 30% of what we throw away and could be composted instead. Making compost keeps these materials out of landfills where they take up space and release methane, a potent greenhouse gas that contributes to climate change. Furthermore, compost enriches soil, helping retain moisture and suppress plant diseases and pests. It reduces the need for chemical fertilizers and encourages the production of beneficial bacteria and fungi. Composting can be done at an industrial scale, such as with yard waste collected from homes in a city. It can also be done at home.

Figure $19.4.d$): Compost is a nutrient-rich substance formed from decomposition of yard and food waste that enriches garden soil. Image by EPA (public domain).

All composting requires three basic ingredients: browns, greens, and water. "Browns" are materials such as dead leaves, branches, and twigs. "Greens" are materials such as grass clippings, vegetable waste, fruit scraps, and coffee grounds. The brown materials provide carbon for your compost, the green materials provide nitrogen, and the water provides moisture to help break down the organic matter. A compost pile should have an equal amount of browns to greens. Layers of these organic materials with different particle sizes should be alternated.

Backyard Composting

Backyard composting requires a compost bin or pile to be placed in dry, shady spot near a water source (figure $19.4.e$). Brown and green materials are added as they are collected, and larger pieces are chopped or shredded before they are added to the pile. Dry materials are moistened as they are added. Once the compost pile is established, grass clippings and green waste are mixed into the pile when added. When fruit and vegetable wastes are added, they are buried under 10 inches of compost material. Some homeowners cover the top of the compost with a tarp to keep it moist. When the material at the bottom is dark and rich in color, the compost is ready to use. This usually takes anywhere between two months to two years.

Figure $19.4.e$): This compost bin contains food scraps and yard waste. Image by Ben_Kerckx/Pixabay (Pixabay license)

Indoor Composting

For those who do not have the space for an outdoor compost pile, materials can be composted indoors using a special type of bin, which can be purchased at a local hardware store, gardening supplies store, or made at home. Care must be taken to properly manage the compost pile and keep track of what is added such that it does not attract pests or rodents or smell bad. The compost should be ready in two to five weeks.

Interactive Element

Not all food scraps can go into compost. If you want to start a compost pile and are not sure which food scraps are suitable, see the lists on the Environmental Protection Agency website.

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19.5: Data Dive- "Flushable" Wipes

Overview

Ryerson University published a 2019 report titled, Defining “Flushability” for Sewer Use. This publication had the objective of making the public think twice about what you flush down the toilet in order to save money and the environment. In this experiment they tested 101 single use products, some labeled (and some not labeled) flushable. Some of the results of this can be seen in the graph below:

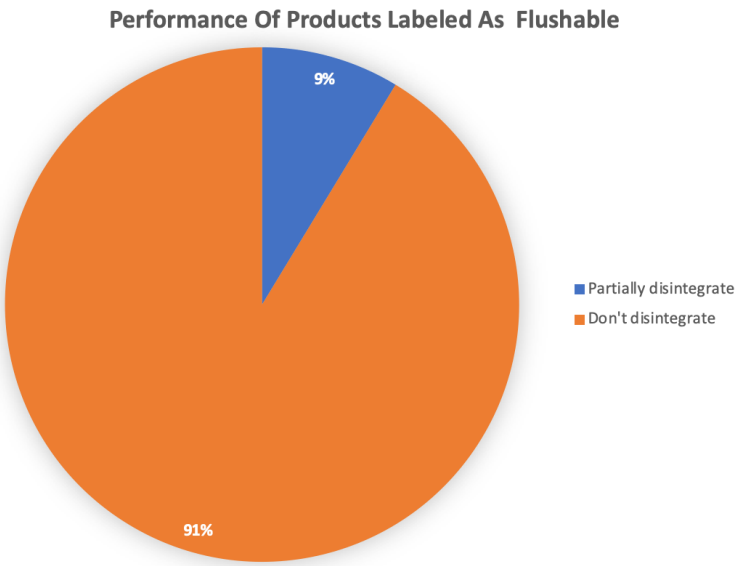

Figure $19.5.a$: Percent of flushable wipes that could pass as flushable. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Khan A, Orr B, Jocksimovie D 2019 Flushability Report.

Questions

1. What type of data is this (qualitative or quantitative)?
2. What question(s) are the authors trying to answer with this graph?
3. What result is this graph illustrating relative to products labeled as “flushable?”
4. Provide a brief reflection for how these results make you feel and what they make you think about?
5. Do you think there should be a policy put in place that places restrictions on what the word “flushable” means? Why?

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19.6: Review

Summary

After completing this chapter you should be able to...

- Distinguish between biodegradable and nondegradable waste.
- Provide examples of hazardous waste.
- List the major waste generating processes globally.
- Compare the volume of waste generated per person per day in the U.S. with other countries around the world.
- Define municipal solid waste and describe its composition in the U.S.
- Compare open dumps, sanitary landfills, and incineration, outlining the advantages and disadvantages of each approach.
- Explain how trash enters the ocean and how it harms marine life.
- Explain the waste management hierarchy.
- List the four R's and provide examples of each.
- Explain the benefits and process of composting.

Solid waste refers to a variety of discarded materials that are deemed useless and discarded by humans. Waste may be easily broken down (**biodegradable**) or **nondegradable**. **Hazardous waste** is harmful to human health. Examples include batteries, cleaners, and **e-waste**. Agriculture, industry, and mining generate most of the world's waste. **Municipal solid waste** (MSW) is discarded from residences, businesses, and city buildings, and the U.S. generates more MSW per person per day than most countries around the world.

Three strategies for disposing of waste are open dumps, sanitary landfills, and incinerators. **Open dumps** cause disease spread, air pollution, and water pollution, and are thus illegal in the U.S. About half of the MSW in the U.S. goes to **sanitary landfills**, which compact trash and seal it to prevent pollution. **Incinerators** burn trash, which reduces its volume while generating energy.

Ocean dumping and escape of trash from overfilled bins and open dumps has contaminated the ocean with many plastics. These break into small pieces and form **garbage patches**. Plastic in the ocean can trap, poison, or otherwise harm marine life.

The **waste management hierarchy** diagrams the priorities of waste reduction. Source reduction and recycling are key to limiting waste and mitigating its environmental impacts. However, a large volume of trash goes to disposal, the least preferred method for handling waste. Individuals can limit their own waste by employing the **four R's**: **refuse**, **reduce**, **reuse**, and **recycle**. **Composting** at home also reduces food and yard waste.

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20: POLLUTION

Chapter Hook

In the midst of the COVID-19 pandemic many people in the United States were feeling the fatigue of wearing face masks for protection. However, people in the United States should consider themselves lucky that normally their air is clean enough that face masks are only really necessary for people who have sensitive immune systems (to things like the flu season, wildfire season, and allergy season). Thus, masks are not a normal part of life for people in the United States. However, in some places around the world, masks are normally worn due to heavy air pollution. For example, people living or working in the cities of China wear masks as a daily part of life. Every day, people wear masks to protect their lungs. Although pollution is decreasing due to policies set in place to fight pollution, it hasn't yet made masks an unnecessary part of everyday life.

Figure $20.a$: Mask garbage. Image by Pixabay (Public Domain).

- Pollution

20.1: Water Pollution

20.1.1: Water Pollutants and Their Sources

20.1.2: Water Treatment

20.1.3: Mitigating Water Pollution

20.2: Air Pollution

20.2.1: Ozone Depletion

20.2.2: Acid Deposition

20.3: Data Dive- Plastic in World Oceans

20.4: Review

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20.1: WATER POLLUTION

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. Contaminants may come from from direct or indirect sources, or captured from air by rain. The level of water pollution depends on the abundance of the pollutant, the ecological impact of the pollutant, and the use of the water.

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20.1.1: Water Pollutants and Their Sources

20.1.2: Water Treatment

20.1.3: Mitigating Water Pollution

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20.1.1: Water Pollutants and Their Sources

Although natural processes such as volcanic eruptions or evaporation sometimes can cause water pollution, most pollution is derived from human, land-based activities. Pollutants can spread through different water reservoirs, as the water carrying them progresses through stages of the water cycle (figure $20.1.1.a$). **Residence time** (the average time that a water molecule spends in a reservoir) is key 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.

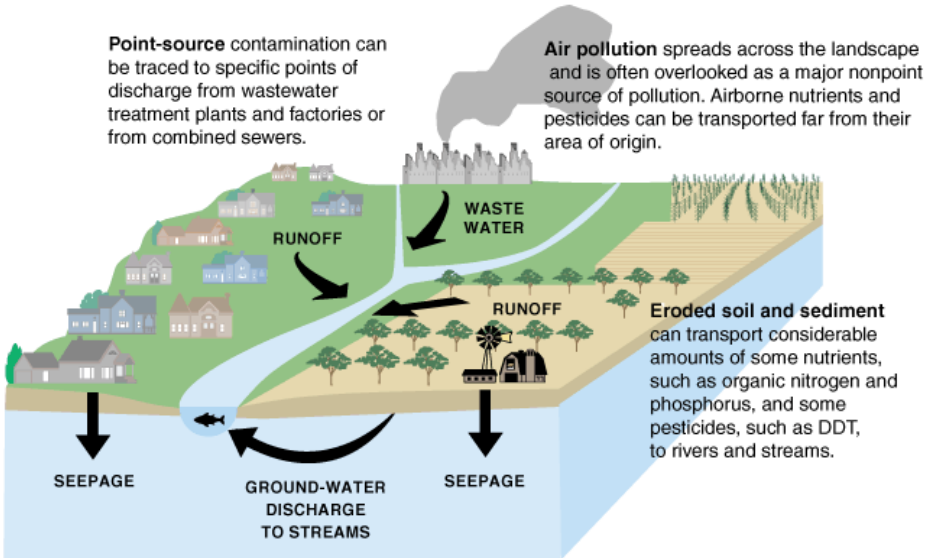

Figure $20.1.1.a$: Sources of some water pollutants and movement of pollutants into different water reservoirs of the water cycle (such as rivers and aquifers). Point source contamination can be traced to specific points of discharge. Air pollution is an example of nonpoint source contamination because contaminants are throughout the air and landscape, ultimately entering the water from multiple locations. Eroded soil and sediment are another source of nonpoint source pollution. Image by USGS (public domain).

Water can be contaminated by various human activities or by existing natural features, like mineral-rich geologic formations. Agricultural activities, industrial operations, landfills, animal operations, and small and large scale sewage treatment processes, among many other things, all can potentially contribute to contamination. As water runs over the land or infiltrates into the ground, it dissolves material left behind by these potential contaminant sources. The risks and type of remediation for a contaminant depend on the type of chemicals present.

Point source pollution can be attributed to a single, definable origin. For example, animal factory farms (figure $20.1.1.b$) raise a large number and high density of livestock such as cows, pigs, and chickens. 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 also be major point sources of pollutants. During heavy rain, storm water runoff may exceed sewer capacity, causing it to back up. This spills untreated sewage directly into surface waters (figure $20.1.1.c$). Other examples include pipes from factories, waste disposal sites, storage tanks, and chemical spills.

Figure 20.1.1.b: 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

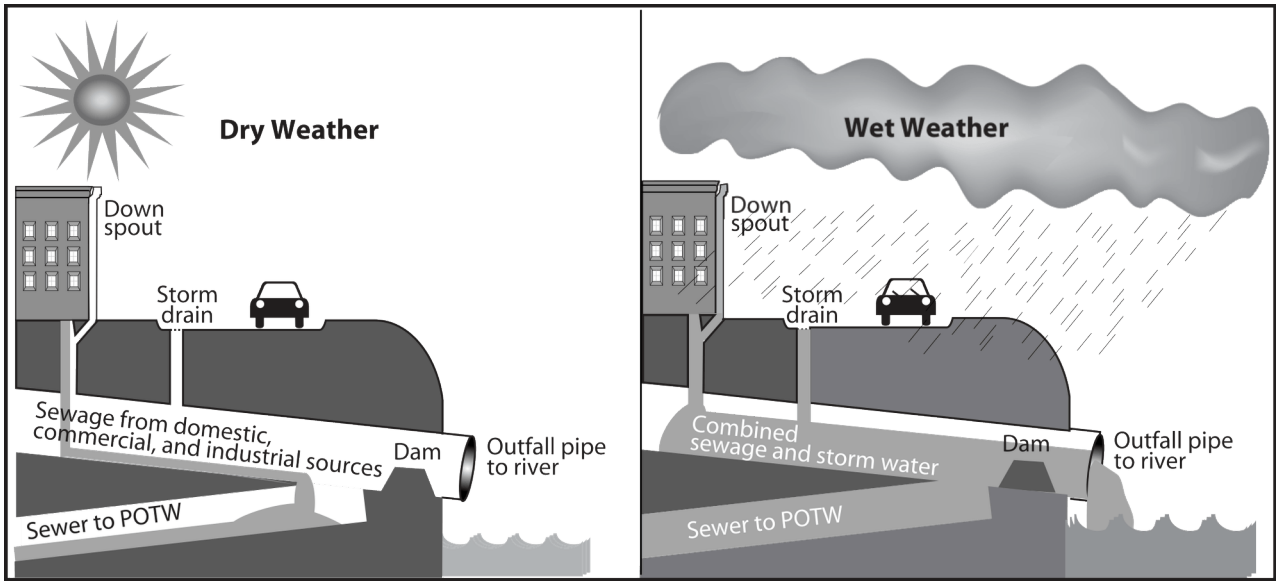

Figure 20.1.1.c: A combined sewer system is a possible major point source of water pollution during heavy rain due to overflow of untreated sewage. Sewage from domestic, commercial, and industrial sources enter the system through the down spout and storm water enters through the storm drain. During dry weather (and small storms), all sewage is handled by the publicly owned treatment works (POTW). A dam prevents raw sewage from flowing into a water body through the outfall pipe. During wet weather (large storms), the relief structure allows some of the combined sewage and storm water to be discharged untreated to an adjacent water body. Image by U.S. Environmental Protection Agency (public domain).

Nonpoint source pollution is from multiple dispersed sources. The whole of the contribution of pollutants is harmful, but the individual components may not reach harmful concentrations. Nonpoint sources of pollution include agricultural fields, cities, and abandoned mines. Rainfall runs over the land and through the ground, picking up pollutants from throughout the **watershed** (including areas of land and smaller streams that drain into a particular body of water). These pollutants might include 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 by runoff 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.

According to a 2016 report, there were 20,912 cases of impaired water bodies in the United States, which means they could neither support a healthy ecosystem nor meet water quality standards (table 20.1.1.a). Selected causes of impairment (water

pollutants) are discussed below, categorized according to whether they arise from chemical, biological, or physical processes.

Table $20.1.1.a$***:*** *The leading causes of impaired bodies of water in the United States in 2016. Data from EPA (public domain).*

Cause of Impairment	Number of Impaired Bodies of Water
Polychlorinated biphenyls (PCBs)	3,712
Pathogens	2,248
Nutrients	2,228
Mercury	2,138
Metals (other than mercury)	2,075
Cause unknown- impaired biota	1,852
Organic enrichment/oxygen depletion	1,281
Turbidity	1,175
Pesticides	795
Salinity/total dissolved solids/chlorides/sulfates	576
pH/acidity/caustic conditions	489
Sediment	453
Temperature	358
Total toxics	282
Algal growth	174
Cause unknown	159
Dioxins	136
Toxic organics	127
Toxic inorganics	99

Chemical Pollutants

Chemical pollution from agriculture, industry, cities, and mining threatens global water quality. Air pollutants from these activities can also enter bodies of water (and become water pollutants) through dry deposition, precipitation, and runoff. Some chemical pollutants have serious and well-known health effects, whereas many others have poorly known long-term health effects.

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.

Organic Pollutants

Organic pollutants include herbicides and pesticides, pharmaceuticals, fuel (such as oil spills), industrial solvents and cleansers, and synthetic hormones associated with pharmaceuticals. These synthetic hormones can act as **endocrine disruptors**. Many are **persistent organic pollutants** (POPs), which are long-lived in the environment, biomagnify through the food chain, and can be toxic. As previously mentioned, DDT (pesticide), dioxin (herbicide by-product), and PCBs (polychlorinated biphenyls, which were used as a liquid insulator in electric transformers), are all POPs.

An example of organic chemical contamination is the Love Canal, in Niagara Falls, New York (Figure $20.1.1.d$). From 1942 to 1952, the Hooker Chemical Company disposed of over 21,000 tons of chemical waste, including chlorinated hydrocarbons, into a canal and covered it with a thin layer of clay. Chlorinated hydrocarbons are a large group of organic chemicals that have chlorine functional groups, most of which are toxic and carcinogenic to humans (DDT and PCBs are an examples.) The company sold the land to the New York School Board, who developed it into a neighborhood. After residents began to suffer from serious health ailments and pools of oily fluid started rising into residents' basements, the neighborhood had to be evacuated. This site became a U.S. Environmental Protection Agency **Superfund Site**, a site with federal funding and oversight to ensure its cleanup.

Figure $20.1.1.d$: The Love Canal in Niagra Falls, New York. Image by Environmental Protection Agency (public domain).

Inorganic Pollutants

Inorganic pollutants (figure $20.1.1.e$) include nutrients like nitrate (NO_3^-) and phosphate (PO_4^{3-}), heavy metals, chloride (Cl^-), and radioactive isotopes released from mining or nuclear accidents (such as cesium, iodine, uranium, and radon gas). Nutrients can be from geologic material, like phosphorus-rich rock, but are most often sourced from fertilizer and animal and human waste. Untreated sewage and agricultural runoff concentrate nitrogen and phosphorus which are essential for the growth of microorganisms. Nutrients like nitrate and phosphate in surface water can promote the growth of microbes, like blue-green algae (cyanobacteria), which in turn deplete dissolved oxygen (O_2) and produce toxins. This process is known as **eutrophication** (discussed below as well as previously in Biogeochemical Cycles, Threats to Biodiversity, and Industrial Agriculture).

Figure $20.1.1.e$: This scientist demonstrates how to test water quality, and part of this involves measuring levels of inorganic pollutants. Image by Erin Gleeson (CC-BY).

Examples of heavy metals include arsenic, mercury, lead, cadmium, and chromium, and they can bioaccumulate and biomagnify through the food chain. Arsenic (As) 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 enters the water supply naturally from weathering of mercury-rich minerals and, like mercury, 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 mercury 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.

Salt, typically sodium chloride, is a common inorganic contaminant. It can be introduced into groundwater from natural deposits or from anthropogenic sources like the salts applied to roads in the winter to keep ice from forming (figure $20.1.1.f$). Salt contamination can also occur from **saltwater intrusion**, where cones of depression around fresh groundwater pumping near ocean coasts induce the encroachment of salt water into the freshwater body.

Figure $20.1.1.f$: A snow plow and road salt application truck that is used to clear snow and ice from roadways for improving traffic and pedestrian safety. The use of salt to deice pavement can be harmful to aquatic life in urban streams. Image and caption (modified) from USGS (public domain).

The acidity or alkalinity of a body of water can also impact its quality. **pH** is a measure of the concentration of hydrogen ions (protons) in a solution, which determines how acidic or basic (alkaline) a solution is. Acidic solutions have a high hydrogen ion concentration and a pH less than 7, and basic solutions have a pH of greater than 7. The pH of freshwater usually ranges from 5 to 9, and salt water is slightly basic (pH = 8.2) in a healthy ecosystem. When conditions are too acidic, some aquatic animals cannot reproduce, and calcium carbonate structures (clams, snails, corals, etc.) dissolve. Acid deposition is further discussed later in this chapter, and ocean acidification is discussed in the next chapter.

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 prevent the minerals from precipitating on surfaces (figure $20.1.1.g$). Hard water develops naturally from the dissolution of calcium and magnesium carbonate minerals in soil; it does not have negative health effects in people.

Figure $20.1.1.g$: Overly hard water (high calcium content) can cause film on glassware. Image by Liz Meimann/Iowa State Univ. (public domain).

Biological Pollutants

Pathogens (infectious microorganisms or viruses) 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 (O_3), by boiling, or by treating the sewage in the first place.

Physical Sources of Pollution

Trash, sediments, and thermal pollution arise from physical sources of pollution (figure $20.1.1.h$). Trash was discussed extensively in Solid Waste Management. Excess sediments enter bodies of water when various land uses, such as mining, deforestation, and agriculture increases erosion. Sediments can carry toxins or excess nutrients with them, and they cloud the water (resulting in **turbidity**). Turbidity obstructs aquatic plants from accessing sufficient sunlight. Thermal pollution occurs when water temperature exceeds its natural range. Many power plants (such as coal, natural gas, nuclear, etc.) rely on water from the environment for cooling. This water is released back into bodies of water at a higher temperature than usual. High temperature disrupt aquatic organisms for several reasons; one is that warmer waters cannot hold as much dissolved oxygen (see below; figure $20.1.1.i$). Dams can also raise water temperature to the detriment or the organisms that live there.

Figure $20.1.1.h$: Water Pollution. Obvious water pollution in the form of floating debris; invisible water pollutants sometimes can be much more harmful than visible ones. Image by Stephen Codrington (CC-BY).

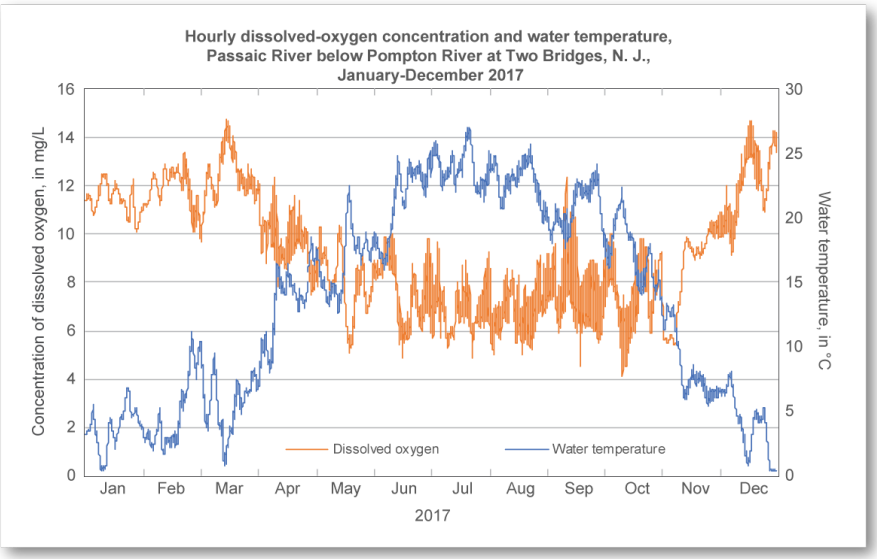

Figure $20.1.1.i$: Water temperature affects dissolved oxygen concentrations in bodies of water. From January to December 2017, water temperature (blue) increases in summer months and then decreases. Dissolved oxygen levels (orange) dips in the summer when temperature increases. Image and caption (modified) from USGS (public domain).

Biochemical Oxygen Demand, Hypoxia, and Eutrophication

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. Decomposers, such as bacteria and fungi, also conduct cellular respiration and consume oxygen as they break down dead organic matter.

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) 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 dissolved oxygen content is restored. The dissolved oxygen content in such a river ranges from 10 to 14 ppm. When biological oxygen demand is low, clean-water fish such as trout thrive (figure $20.1.1.j$).

Figure $20.1.1.j$: Left: Fish like rainbow trout thrive under low biological oxygen demand and ample levels of dissolved oxygen. Right: Fish like carp thrive under high biological oxygen demand and low dissolved oxygen levels. Left image by Engbretson Eric/U.S. Fish and Wildlife Service (public domain). Right image by X posid (public domain).

A polluted water body with respect to BOD 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 oxygen content is ≤ 5 ppm. Biological oxygen demand is high, and fish tolerant to low oxygen levels, such as carp and catfish dominate (figure $20.1.1.k$).

Excessive nutrients, particularly nitrogen (N) and phosphorous (P), are pollutants closely related to oxygen-demanding waste. Plants and algae require 15-20 nutrients for growth, most of which are plentiful in water. Nitrogen and phosphorus 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 nitrogen and phosphorus are major ingredients in most fertilizer.

High concentrations of limiting nutrients, particularly nitrogen (N) and phosphorous (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 (figure $20.1.1.k$). A small percentage of algal species produce toxins that can kill animals, including humans. Exponential growths of these algae are called **toxic algal blooms**.

Figure 20.1.1.k: A cyanobacteria (blue-green algae) bloom in Lake Erie resulting from fertilizer pollution. Image by NASA (public domain).

When the prolific algal layer dies, it becomes oxygen-demanding waste, which can create very low oxygen concentrations in the water (< 2 ppm), 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 (figure 20.1.1.l). Approximately 50% of lakes in North America, Europe, and Asia are negatively impacted by eutrophication. Eutrophication and hypoxia are difficult to combat because they are caused primarily by nonpoint source pollution, which is difficult to regulate, and nitrogen and phosphorus are difficult to remove from wastewater.

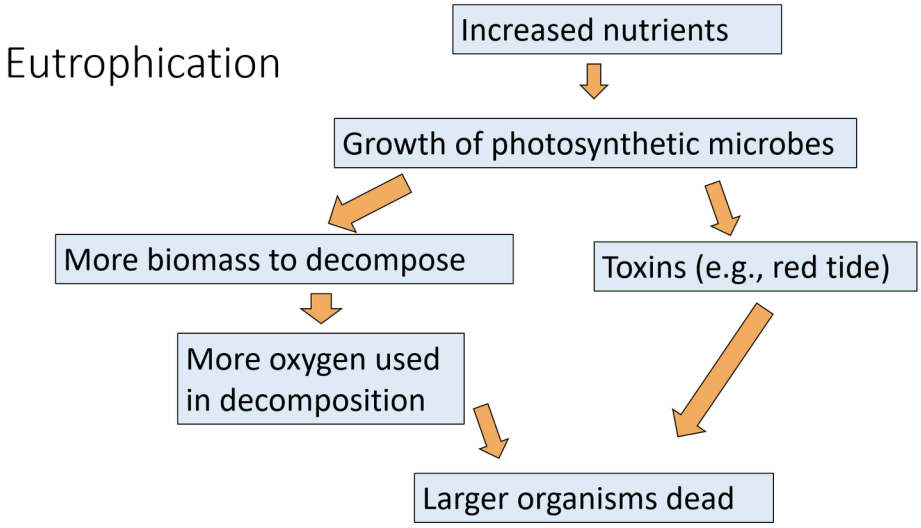

Figure 20.1.1.l: The process of eutrophication. During eutrophication, increased nutrients causes the growth of photosynthetic microbes resulting in more biomass to decompose. More oxygen is used in decomposition, resulting in the death of larger organisms. The growth of photosynthetic microbes also leads to toxins (for example, those produced during red tides), which also leads to the death of larger organisms.

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20.1.2: Water Treatment

The most deadly form of water pollution, pathogenic microorganisms that cause waterborne diseases, killed 485,000 million people (mostly in developing countries) in 2017. 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, excess nutrients, 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 wastes generated by some 80% of U.S. households are collected in sewer systems. Each day, the United States processes about 34 billion gallons of wastewater (99.9% of this is water). In 2004, an Environmental Protection Agency (EPA) report estimated that 860 billion gallons of untreated wastewater (raw sewage) escaped into rivers, streams, and the ocean, mainly from combined sewage systems (see Water Pollutants and Their Sources). As of 2020, the EPA has assessed nearly 96% of the systems responsible for wastewater overflow and addressed them with a civil complaint, enforcement order, or permit requirement. However, in 2017, the EPA estimated that were still 40,000 or more wastewater overflow events, which released raw sewage into bodies of water.

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.

Wastewater Treatment

The sewage that is properly directed to a wastewater treatment plant undergoes several steps: pretreatment, primary treatment, tertiary treatment, and disinfection and discharge (figure $20.1.2.a$). **Pretreatment** involves the screening and removal of sand and gravel. **Primary treatment** involves settling or floatation to remove organic solids, fat, and grease. The undissolved solids in raw sewage to settle out of suspension forming **sludge**. Such **primary treatment** removes only one-third of the biological oxygen demand (BOD) and virtually none of the dissolved minerals. Attempts to use digested sludge as a fertilizer have been hampered by its frequent contamination by toxic chemicals derived from industrial wastes.

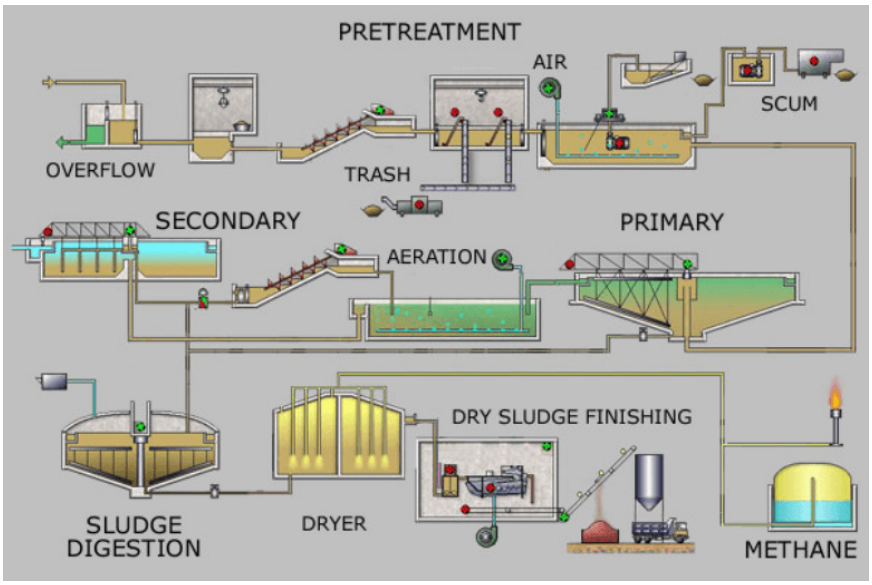

Figure $20.1.2.a$: Steps at a wastewater treatment plant. The numerous processing steps at a conventional sewage treatment plant include pretreatment (screening and removal of sand and gravel), primary treatment (settling or floatation to remove organic solids, fat, and grease), secondary treatment (aerobic bacterial decomposition of organic solids), tertiary treatment (bacterial decomposition of nutrients and filtration), disinfection (chemical or UV treatment to kill bacteria), and either discharge to surface waters or reuse. Only pretreatment, primary treatment, secondary treatment, and sludge digestion are shown here. Sewage initially enters pretreatment, though some may escape due to overflow. Screening removes larger components, which enter the trash. Air is added, the top layer (scum) is removed, and sludge (solids that settle to the bottom) are removed during primary treatment. Further aeration is required for secondary treatment to supply oxygen to the aerobic bacteria that break down organic components in the fluid. More sludge is removed. The sludge removed during primary and secondary treatment undergo sludge digestion. This involves a dry, dry sludge finishing, and methane production. Image by Leonard G. (CC-BY-SA).

Next, the organic solids in the effluent are decomposed by **aerobic** (oxygen-requiring) bacteria in **secondary treatment**. Here the effluent is brought in contact with oxygen. Aerobic microorganisms break down much of the organic matter to harmless substances such as carbon dioxide. Primary and secondary treatment together can remove up to 90% of the BOD. After chlorination to remove its content of bacteria, the effluent from secondary treatment is returned to the local surface water.

The concentrated organic solid produced during primary and secondary treatment (sludge) 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.

Although the combination of primary and secondary treatment removes most of the organic matter in sewage, lowering BOD, most of the nitrogen and phosphorus in sewage remains in the effluent (liquid portion of the sewage). In **tertiary treatment**, bacteria are used to remove the remaining nutrients, and filtration occurs. Additionally, several techniques are available to remove dissolved salts from sewage effluent, but all are quite expensive.

During **disinfection**, further treatment involves disinfection with chlorine, ozone, ultraviolet light, or bleach to kill most microbes. Finally, the treated water is **discharged** to surface waters (usually a local river) or **reused** for some other purpose, such as irrigation, habitat preservation, and artificial groundwater recharge

Septic Tank System

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 $20.1.2.b$) include a sewer line (inlet) from the house, a septic tank, and the drain field. The **septic tank** is a large container where sludge settles to the bottom, where microorganisms decompose the organic solids anaerobically. The **drain field** is a 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.

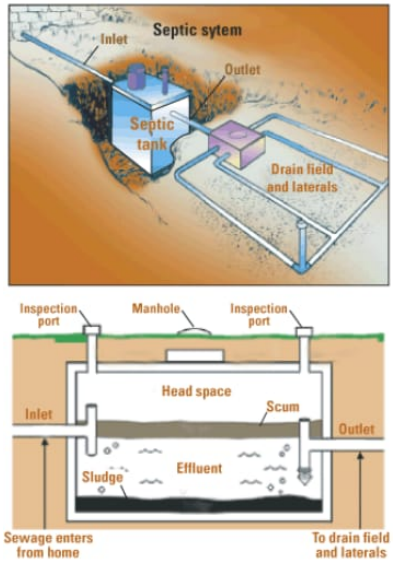

Figure $20.1.2.b$: A septic tank system for sewage treatment. The inlet transports sewer to the septic tank (top). Inside the septic tank (bottom), sludge settles to the bottom of the liquid effluent. Anaerobic bacteria digest the sludge. Scum floats on the top of the effluent, and the air above it is called the headspace. Two inspection ports extend above the septic tank, which is buried underground. It is also accessible through a manhole. Effluent leaves the outlet into the drain field, which contain pipes (laterals) with small holes in them. The effluent is released and can infiltrate into the ground and be further purified by bacteria. Image by United States Geological Survey (public domain).

Addressing Water Treatment Globally

For many developing countries, financial aid is necessary to build adequate wastewater treatment facilities. The World Health Organization estimates an estimated cost savings at least $5 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.

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20.1.3: Mitigating Water Pollution

Water pollution can be mitigated through regulation, bioremediation, and watershed management.

Regulation

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 (figure $20.1.3.a$). 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** (CWA). 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. The CWA regulates pollution from a single source such as that from industry or sewage treatment plants by setting pollution standards (maximum levels of each pollutant that can be in bodies of water or released at a time). United States water quality improved significantly as a result, but as there is still more work to be done.

Figure $20.1.3.a$: Cuyahoga River on fire in 1969. Image from USEPA Environmental-Protection-Agency (public domain).

Remediation

Remediation is the act of cleaning contamination. Biological remediation (**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 nontoxic substances". This type of remediation is usually used on organic chemicals but also works on reducing or oxidizing inorganic chemicals like nitrate. **Phytoremediation** is a type of bioremediation that uses plants to absorb the chemicals over time.

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. Several species of bacteria can carry out the biotransformation of toxic mercury into nontoxic forms. These bacteria, such as *Pseudomonas aeruginosa*, can convert a charged form of mercury (Hg^{2+}) to an uncharged form (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. 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 break the oil into droplets, making it more accessible to the bacteria that degrade the oil. 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 (those that do not readily evaporate) in oil can be degraded within one 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 $20.1.3.a$: (a) Cleaning up oil after the Exxon Valdez spill in Alaska (1989), 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 microorganisms for bioremediation of hydrocarbons also has the advantage of breaking down contaminants at the molecular level, as opposed to simply chemically dispersing the contaminant.

Chemical remediation uses the introduction of chemicals to remove the contaminant or make it less harmful. One example is reactive barriers, a permeable wall in the ground or at a discharge point that chemically reacts with contaminants in the water. Reactive barriers made of limestone can increase the pH of acid mine drainage, making the water less acidic and more basic, which removes dissolved contaminants by precipitation into a solid form. **Physical remediation** consists of removing the contaminated water and either treating it (aka pump and treat) with filtration or disposing of it. All of these options are technically complex, expensive, and difficult, with physical remediation typically being the most costly.

Watershed Management

Watershed management involves reducing chemicals applied to land in the watershed (which will drain into a body of water) and runoff of those chemicals (figure $20.1.3.b-c$). This strategy is more effective for nonpoint source pollution than setting pollution standards (as the CWA does) because it does not require each source of pollution be identified.

Figure $20.1.3.b$: While some watersheds are relatively small, others encompass thousands of square miles and may contain streams, rivers, lakes, reservoirs, and underlying groundwater that are hundreds of miles inland. Shown here is an aerial view of Drakes Bay, part of California's Tomales-Drake watershed. Image and caption (modified) from Brian Cluer, NOAA Fisheries West Coast Region, California Coastal Office (public domain).

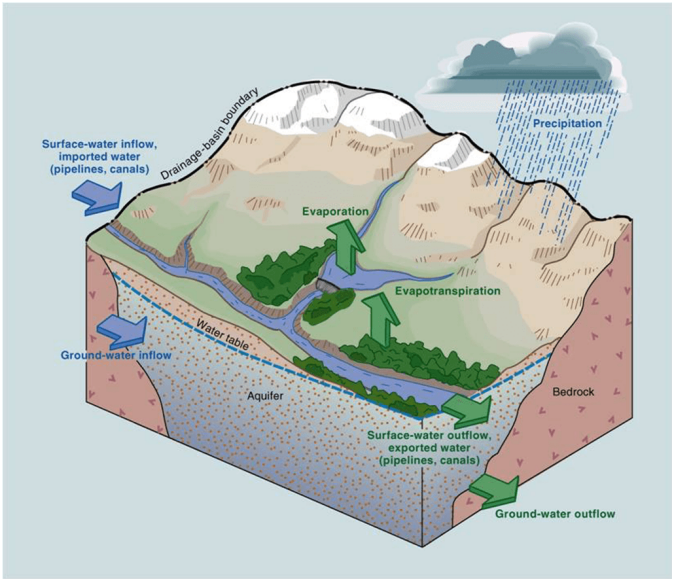

Figure $20.1.3.c$: Diagram of a watershed, the area that drains into a body of water. The drainage-basin boundary defines the edges of the watershed. Precipitation falls on the watershed. Some reenters the atmosphere through evaporation or evapotranspiration. The water collects into smaller streams, which drain into a larger river. Additionally, surface water can enter the watershed (surface-water inflow) as water imported through pipelines or canals. Surface water exits the watershed (surface-water outflow) as water exported through pipelines canals. Similarly, ground-water inflow enters the system, and ground-water outflow exits the system. Ground water is stored in the aquifer underground, and the water table marks upper level of groundwater in the aquifer. Image from Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, : Water budgets: Foundations for effective water-resources and environmental management: U.S. Geological Survey Circular 1308.

Maintaining or restoring **riparian areas** (riparian zones) is key to watershed management (figure $20.1.3.d$). These are areas of land close enough to a body of water to be affected by that body of water, for example, the lush region of vegetation surrounding a river. Riparian areas provide many ecosystem services that promote water quality and limit pollution. The vegetation absorbs nutrients that could otherwise cause eutrophication. It also provide shade, keeping the water cool and increasing its capacity to hold dissolved oxygen. The roots of the vegetation cling to soil, combating erosion. Additionally, roots and low-lying plants slow the flow of run-off, promoting infiltration. High infiltration rates have several benefits: (1) less runoff is available to bring pollution to the river, lake, or bay, (2) pollutants will be filtered from the runoff as it soaks into the ground, and (3) aquifers are replenished.

Figure $20.1.3.d$: Riparian areas reduce water pollution by absorbing nutrients, keeping water cool, limiting erosion, and promoting infiltration. Image by BLM (public domain).

Watershed management plans typically leave undisturbed riparian vegetation directly adjacent to a body of water (figure $20.1.3.e$). Next (moving away from the water), could be managed forest followed by agriculture. The most intensive agriculture should be farthest from the body of water, particularly when pesticides and fertilizers are in use.

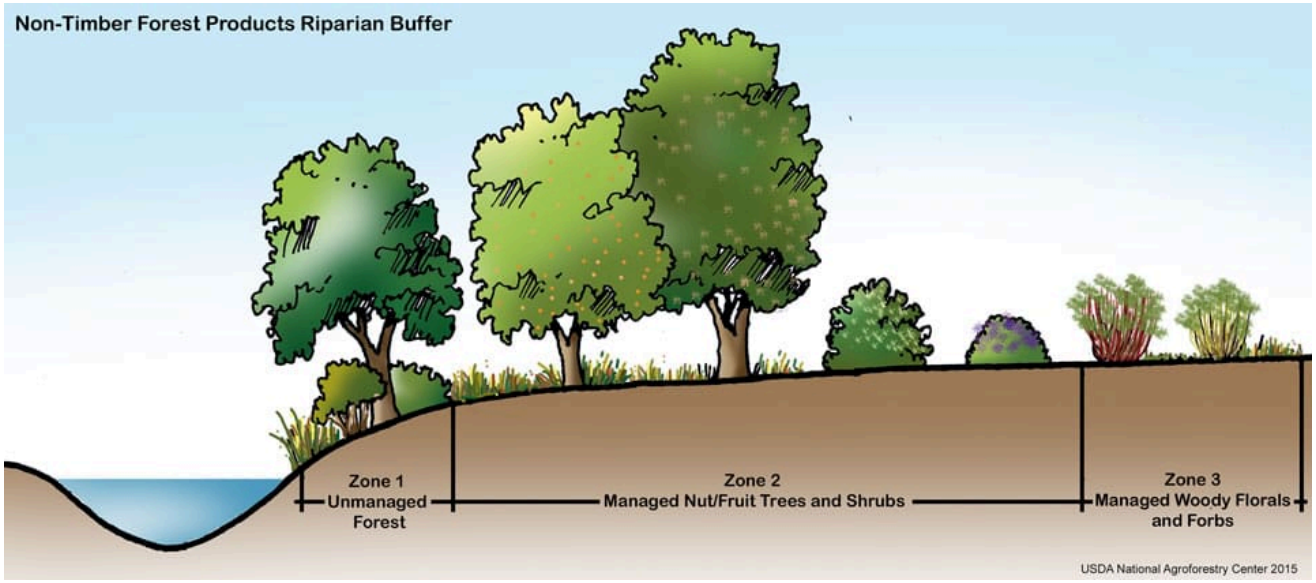

Figure $20.1.3.e$: Although riparian forest buffers are often designed primarily for water quality benefits, these practices can also include woody species that provide products such as nuts, fruit, and decorative woody florals. These are examples of non-timber forest products. Zone 1, which is closest to the river, is unmanaged forest. Zone 2 contains managed nut or fruit trees and shrubs. Zone 3 contains managed woody florals and forbs. (Forbs are non-woody plants excluding grasses.) Image and caption by USDA National Agroforestry Center (public domain).

In urban areas can also be carefully structured to limit water pollution. Rain gardens next to buildings are areas with soil and vegetation that promote infiltration. Permeable pavement, which allows water to pass through it, also promotes infiltration, and reduces runoff, creating fewer opportunities for the water to acquire pollutants from washing over a dirty street.

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20.2: AIR POLLUTION

Air pollution occurs in many forms but can generally be thought of as gaseous and particulate contaminants that are present in the earth's atmosphere. Chemicals discharged into the air that have a direct impact on the environment are called **primary pollutants**. These primary pollutants sometimes react with other chemicals in the air to produce **secondary pollutants**.

Air pollution is typically separated into two categories: outdoor air pollution and indoor air pollution. **Outdoor air pollution** involves exposures that take place outside of the built environment. Examples include fine particles produced by the burning of coal, noxious gases such as sulfur dioxide, nitrogen oxides and carbon monoxide; ground-level ozone and tobacco smoke. **Indoor air pollution** involves exposures to particulates, carbon oxides, and other pollutants carried by indoor air or dust. Examples include household products and chemicals, out-gassing of building materials, allergens (cockroach and mouse dropping, mold, pollen), and tobacco smoke.

This video summarizes the causes, consequences, and solutions to air pollution.

YouTube Video

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

View this YouTube Video online

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 (figure $20.2.a$), 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".

Figure 20.2.a: Smoke from the Camp fire in November of 2018 covers much of Northern California and extends over the Pacific Ocean. Image by NASA Earth Observatory/Lauren Dauphin (public domain).

Criteria Air Pollutants

The Environmental Protection Agency has identified six common air pollutants called **criteria air pollutants**. They 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 nitrogen oxides (NO_X) and the gaseous oxygen (O_2) in the atmosphere react in the presence of sunlight. It also forms when nitrogen oxides and volatile organic compounds (VOCs) react. 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. 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. Examples of human-generated particulate matter are from combustion (such as burning wood or coal) and mining (which releases dust). Wildfires or wind erosion are natural sources of particulate matter. 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. Furthermore, particles that are 2.5 micrometers in diameter or smaller can pass from the lungs into the bloodstream, through which they are transported to various organs 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 vehicles. However, volcanic eruptions and wildfires also release carbon monoxide. Carbon monoxide 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 oxides** (NO_X) are a group of highly reactive gasses, which includes nitrogen monoxide (NO) and nitrogen dioxide (NO_2). EPA's National Ambient Air Quality Standard uses NO_2 as the indicator for the larger group of nitrogen oxides. Nitrogen oxides forms quickly from emissions from cars, trucks and buses, power plants, and off-road equipment. Additionally, nitrogen oxides are released naturally by certain bacteria. In addition to contributing to the formation of ground-level ozone, and fine particle pollution, nitrogen oxides react in the atmosphere to form nitric acid (HNO_3) and nitrous acid (HNO_2), which are components of Acid Deposition. Nitrogen oxides is linked with a number of adverse effects on the respiratory system.

5. **Sulfur dioxide** (SO_2) is mainly released 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. Volcanoes are a natural source of SO_2. Sulfur dioxide is linked with a number of adverse effects on the respiratory system. It reacts in the atmosphere to form sulfuric acid (H_2SO_4), a component of Acid Deposition.
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. Volcanoes and erosion are natural sources of lead.

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

Addressing Air Pollution

A combination of regulatory, economic, and technological strategies can reduce air pollution. The 1970 **Clean Air Act** is a key federal regulation that has successfully reduced emissions of air pollutants such as lead and sulfur dioxide. The Environmental Protection Agency sets an air quality standard for large emitters of criteria air pollutants, which is the maximum allowable amount of the pollutant that can be released. Each state then develops a plan to comply with these standards. Note that hundreds of air pollutants beyond the six criteria air pollutants are regulated under the Clean Air Act.

Economic incentives make it financially beneficial for individuals, institutions, or companies to use technologies or otherwise take action that limits air pollution. For examples, **green taxes** increase the cost of an environmentally harmful action. For example, Canada levies a green tax on fuel-inefficient vehicles. **Subsidies**, on the other hand reduce the cost of environmentally beneficial choices. For example, the federal solar tax credit in the United States allows homeowners to claim a percentage of the cost of installing solar panels when their filing taxes This amount would thus reduce taxes owed or be issued as a tax

refund. (Increased usage of solar electricity ultimately reduces the need for coal and natural gas power plants, which generate air pollution.)

Tradable permits (**cap-and trade**) is another economic incentive. First, the total allowable amount of emissions for an entity (such as a state or country) is set. Next, emission credits are distributed to potential polluters. Industries that reduce emissions can sell their credits, while those with high emissions may be required. For example, large emitters of greenhouse gases in California must by carbon pollution permits. The purchase of these permits funds the California Climate Credit, which Californians receive as a reduction to their April and October electricity bills.

Finally, a variety of technologies reduce air pollution. For example, air filters and proper ventilation are essential for limiting indoor air pollution. Advances in public transportation (and policies that promote them), and energy-efficient vehicles further reduce air pollution. Electric vehicles also reduce air pollution (figure $20.2.b$), particularly if the the electricity that supplies them comes from a clean, renewable source, such as solar panels. **Catalytic converters** make emissions from standard vehicles less harmful by facilitating chemical reactions. For example, they catalyze reactions that convert nitrogen oxides (NO_X) to nitrogen gas (N_2) and carbon monoxide (CO) to carbon dioxide (CO_2). (While carbon dioxide is a greenhouse gas, it is not directly poisonous as carbon monoxide is.)

Other technologies limit emissions from industry. For example, **smokestack scrubbers** remove some pollutants from power plant emissions before they are released and have reduced sulfur dioxide emissions from burning coal. **Electrostatic precipitators** negatively charge pollutants and remove charged pollutants with a positive electrode (figure $20.2.c$). While electrostatic precipitators were originally developed for industry, smaller versions can be used as air purifiers in homes or businesses.

Figure $20.2.b$: Mass transportation, especially those that use clean energy, reduces air pollution. Image by Mtattrain (CC-BY-SA).

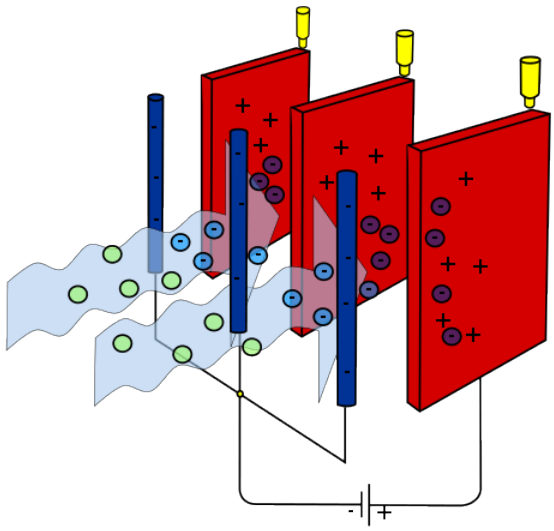

Figure 20.2.c: An electrostatic precipitator. Blue arrows represent the flow of air past metal rods, which negatively charge the pollutants. These are then drawn to positive electrodes (red, flat metal plates), removing the pollutants form the air. Image by Evan Mason (CC-BY-SA).

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- Basic Information about NO_2. Environmental Protection Agency. Accessed 11-04-2021 (public domain).

- Air Pollution

20.2.1: Ozone Depletion

20.2.2: Acid Deposition

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20.2.1: Ozone Depletion

The ozone depletion process begins when **CFCs** (chlorofluorocarbons) and other ozone-depleting substances (ODS) are emitted into the atmosphere (figure $20.2.1.a$). 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 (figure $20.2.1.b$). CFCs were used by industry as refrigerants, degreasing solvents, and propellants.

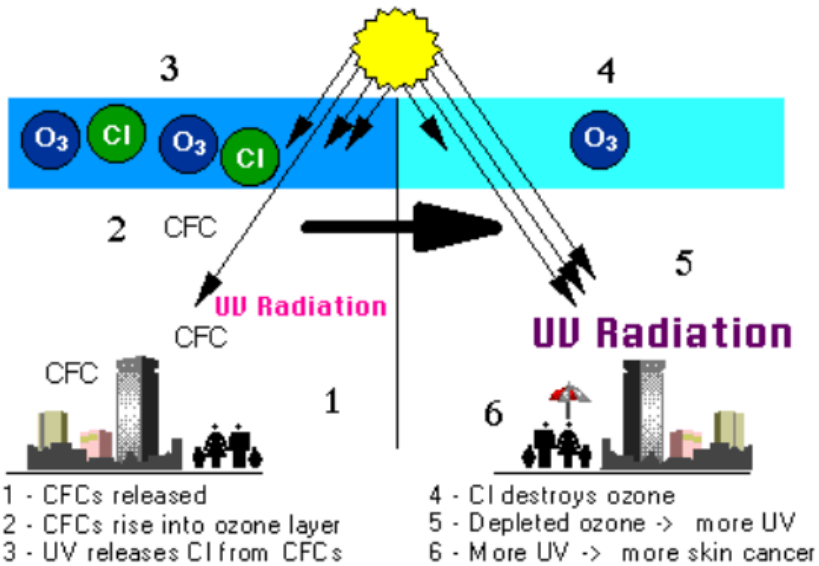

Figure $20.2.1.a$: Strong ultraviolet (UV) light breaks apart the ozone-depleting substances (ODS). The process is as follows: (1) chlorofluorocarbons (CFCs) released, (2) CFCs rise into ozone layer in the stratosphere, which contains ozone (O_3), (3) UV radiation releases chlorine (Cl) from CFCs, (4) Cl destroys ozone, (5) depleted ozone allows more UV radiation to pass through the atmosphere, and (6) more UV radiation causes more skin cancer. Some ODS, including CFCs, hydrochlorofluorocarbons (HCFCs), carbon tetrachloride, and methyl chloroform release Cl atoms. Other ODS, including halons and methyl bromide, release bromine (Br) 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.

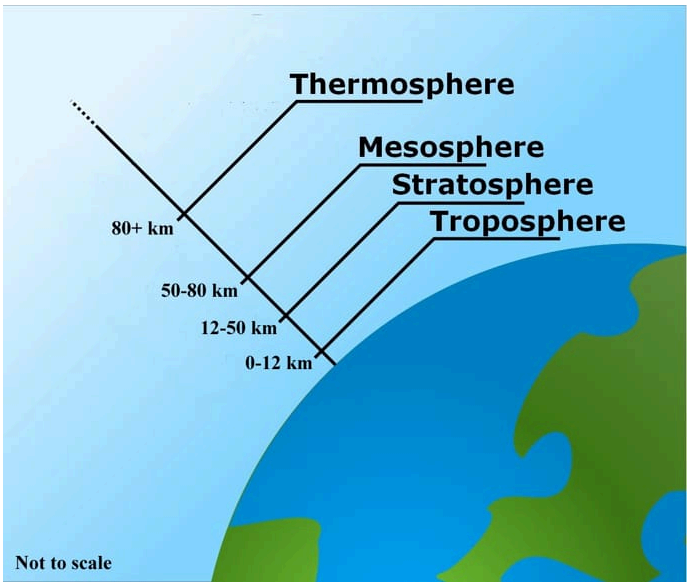

Figure $20.2.1.b$: The layers of the atmosphere. the toposphere is the closest to the Earth's surface (0-12 km). Next, is the stratosphere (12-50 km), mesophere (50-80 km), and thermosphere (80+ km). The outermost layer (the exosphere) is not shown. **Ground-level ozone** in the troposphere is a form of air pollution, but the **ozone layer** in the stratosphere helps filter UV rays. Image by GFDL (CC-BY-SA).

Ozone (O_3) is constantly produced and destroyed in a natural cycle, as shown in figure $20.2.1.c$. 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.

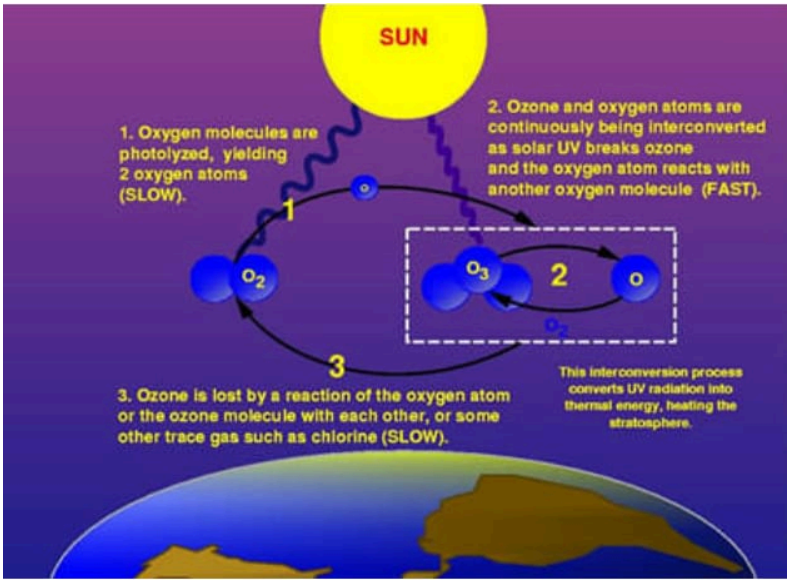

Figure $20.2.1.c$: Because ozone (O_3) filters out a harmful type of ultraviolet radiation (UVB), less ozone means higher UVB levels at the surface. The more the depletion, the larger the increase in incoming UVB. UVB has been linked to skin cancer, cataracts, damage to materials like plastics, and harm 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. The process of the ozone layer filtering UV radiation is as follows: (1) Gaseous oxygen molecules (O_2) are photolyzed (split), yielding two oxygen atoms. This is a slow process. (2) Ozone and oxygen atoms are continuously being interconverted as solar UV breaks O_3 into O_2 and a single oxygen atom (O). The oxygen atom (O) reacts with another O_2 molecule to form O_3. This interconversion is a fast process and converts UV radiation into thermal energy, heating the stratosphere. (3) Ozone is lost by a reaction of the oxygen atom or the ozone molecule with each other, or some other trace gas such as chlorine. This is a slow process.

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. 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.

Because CFCs take many years to reach the stratosphere and can survive there a long time before they break down, the ozone hole did not immediately disappear after CFC emissions were reduced; however, it has been shrinking (figure $20.2.1.d$).

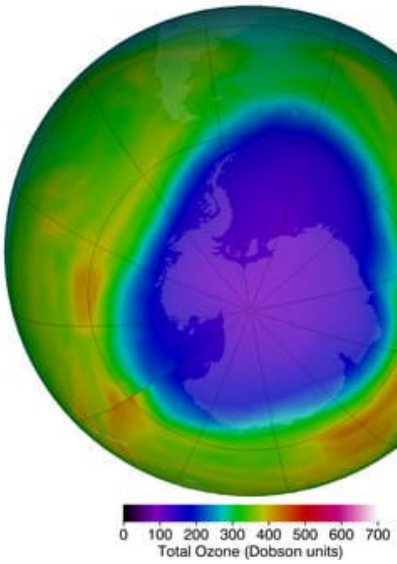

Figure 20.2.1.d: The Antarctic ozone hole that occurs annually in September and October during the Southern Hemisphere spring typically sees much lower ozone levels in than the Arctic. The purples and deep blues show the extent of low ozone levels on October 12, 2018, when they dropped to 104 Dobson units. Image and caption by NASA's Goddard Space Flight Center (public domain).

Interactive Element

The ozone hole is shrinking due to reductions in CFC emissions. You can read more here.

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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20.2.2: Acid Deposition

Acid deposition 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 deposition 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 (figure $20.2.2.a$). Acid deposition 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.

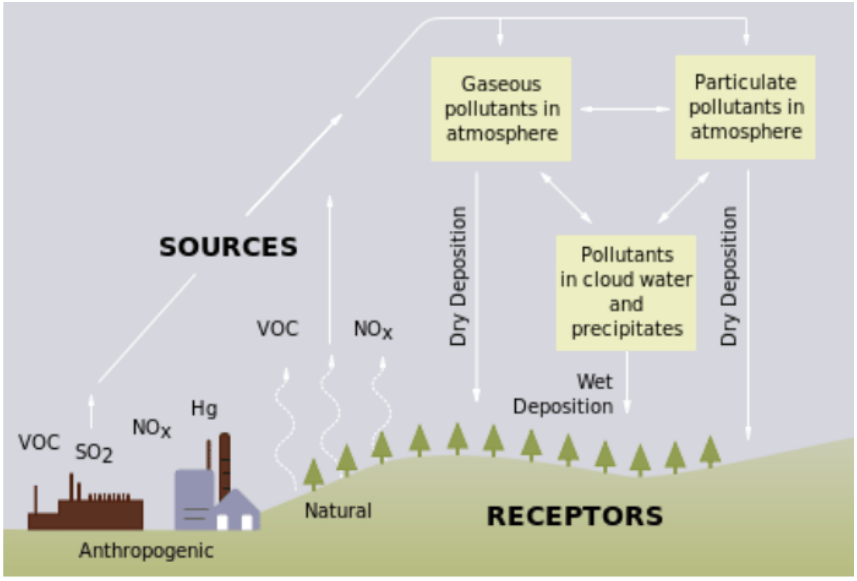
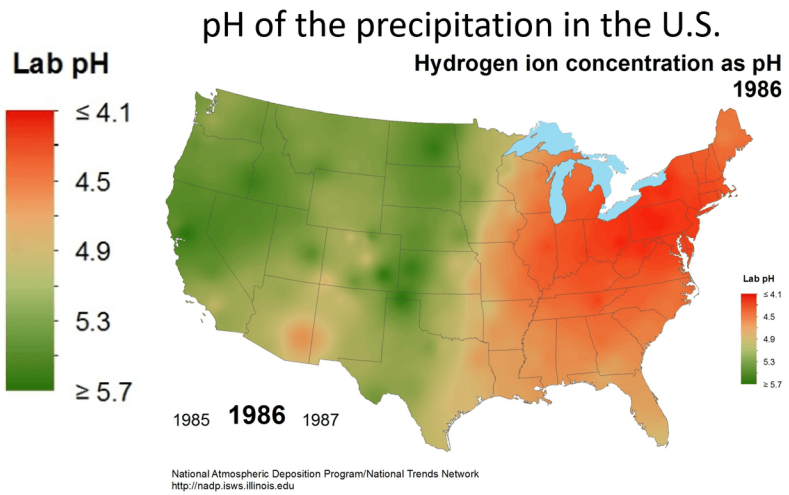


Figure $20.2.2.a$: This diagram shows both anthropogenic and natural sources of acid deposition. Volatile organic compounds (VOCs), sulfur dioxide (SO_2), nitrogen oxides (NO_X), and mercury (Hg) are released, but only SO_2 and NO_X react to form acids. Three categories of pollutants interact with each other. These are gaseous pollutants in the atmosphere, particulate pollutants in the atmosphere, and pollutants in cloud water and precipitates. The former two categories form dry deposition, and the latter forms wet deposition. Acid deposition (both dry and wet deposition) reaches natural areas, which could be terrestrial (as pictured) or aquatic.

Acid deposition 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. The average pH of precipitation in the United States in 1980 was 4.6, but it has been gradually increasing due to reductions in sulfur dioxide and nitrogen oxide emissions (figure $20.2.2.b$).



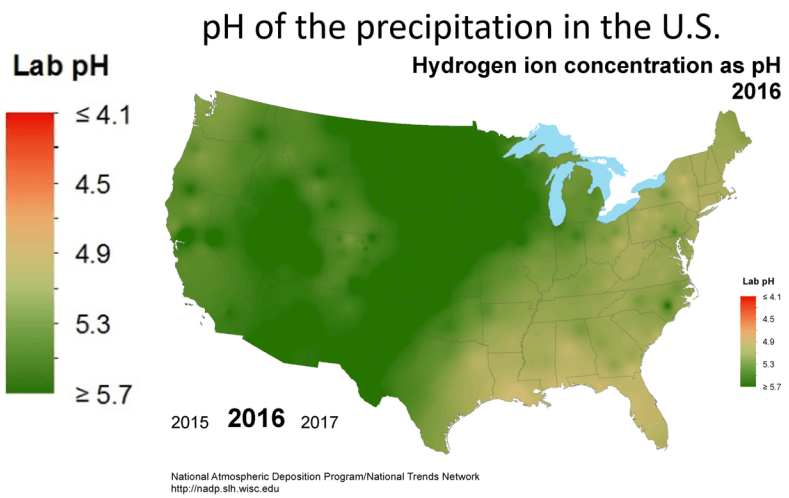


Figure 20.2.2.b: pH measures how acidic or basic a solution is, which depends on the concentration of hydrogen ions. Precipitation is normally slightly acidic, with a pH of around 5.6. (Anything below pH = 7 is considered acidic.) pH of precipitation was even more acidic in much of the East Coast of the U.S. in 1986 (acid deposition) with parts of Michigan, Ohio, Pennsylvania, and New York state reaching a pH of less than or equal to 4.1. The pH of the western United States in 1986 was closer to 5.0. Due to efforts to reduce air pollution, the pH of precipitation has moved closer to normal. By 2016, the pH of the eastern United States had increased to around 4.9, and the pH of the western United States had mostly returned to normal, with many regions having a pH of greater than or equal to 5.7. Images by National Atmospheric Deposition Program (public domain).

Effects of Acid Deposition

Acid deposition 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 deposition 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 deposition 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 deposition. Acid deposition 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 deposition enough to neutralize it. In areas where buffering capacity is low, acid deposition releases aluminum from soils into lakes and streams; aluminum is highly toxic to many species of aquatic organisms. Acid deposition causes slower growth, injury, or death of **forests**. Of course, acid deposition 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 deposition on trees are due to the combined effects of acid deposition and these other environmental stressors.

Acid deposition contributes 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 $20.2.2.c$).

Figure $20.2.2.c$: A gargoyle that has been damaged by acid deposition.

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 deposition—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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20.3: Data Dive- Plastic in World Oceans

Overview

Our World in Data (OWID) is a scientific online publication that focuses on using research and data to help tackle global concerns such as poverty, disease, hunger, climate change, war, and inequitable treatment of our world's most vulnerable and unstable communities. Their website is particularly known for publishing a variety of graphs, some even interactive, to present the research that helps explain causes and consequences of global concerns to the public. One example graph, seen below, illustrates the pathway by which plastic pollution enters the world's oceans:

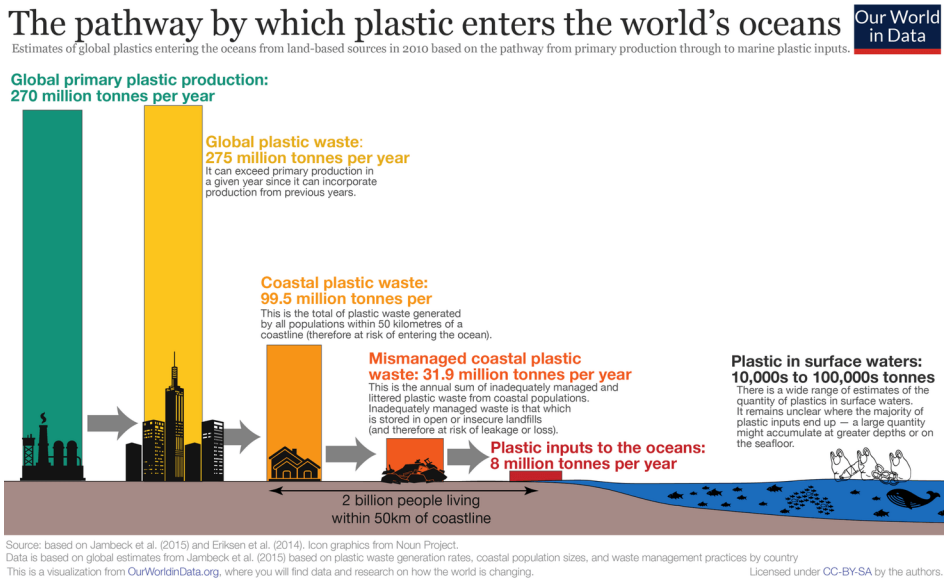

Figure $20.3.a$: Plastic pathway into the ocean by million tonnes per year. Graph by Our World in Data (CC-BY-SA).

Questions

1. Reflect on how this bar graph is different than a standard bar graph. What do you like or not like about it?
2. What is this graph is illustrating about plastic waste?
3. Note that the global plastic waste is higher than the global plastic production. What does that tell you about the amount of plastic not yet classified as "waste"?
4. Provide a brief reflection for how these results make you feel and what they make you think about?
5. How can the results of this graph be used to inform future policies about plastic waste?

Raw Data From Above Graph(s)

Table $20.3.a$**:** Raw data for plastic pathway into the ocean by million tonnes per year. Graph by Our World in Data (CC-BY-SA).

Waste Category	Tonnes Per Year
Global primary waste production	270 million
Global plastic waste	275 million
Coastal plastic waste	99.5 million
Mismanaged coastal plastic waste	31.9 million
Plastic inputs to the oceans	8 million

Waste Category	Tonnes Per Year
Plastic in surface waters	10,000s to 100,000s

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20.4: Review

Summary

After completing this chapter you should be able to...

- Distinguish between point source and nonpoint source water pollution.
- Name and describe common water pollutants, including chemical, biological, and physical pollutants.
- Explain the mechanism of eutrophication.
- Summarize the current state of wastewater treatment globally.
- Describe the process of wastewater treatment, including pretreatment, primary treatment, secondary treatment, tertiary treatment, and disinfection and discharge.
- Summarize strategies for reducing water pollution.
- Identify sources of air pollution.
- List common air pollutants.
- Explain how CFCs caused ozone depletion, and global efforts to address this issue.
- Describe the causes and consequences of acid deposition.

Water pollution may arise from a single origin (**point source pollution**), or it may arise from multiple dispersed sources throughout the **watershed** (**nonpoint source pollution**). Water pollutants may be **chemical**, **biological**, or **physical**. **Oxygen-demanding waste** increases **biological oxygen demand** and causes **hypoxia**, depriving aquatic organisms of oxygen. This results from **eutrophication**, in which excess nutrients cause **algal blooms**.

Pathogens are the most deadly form of water pollution. They cause waterborne diseases, killing 485,000 people 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 **wastewater treatment**. Strategies to reduce water pollution in general include the **Clean Water Act**, **remediation**, and **watershed management**.

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 air 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 ozone depletion process begins when **chlorofluorocarbons** (CFCs) and other **ozone-depleting substances** (ODS) are emitted into the atmosphere. Reductions in stratospheric ozone levels lead to higher levels of harmful ultraviolet radiation, particularly 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. The **Montreal Protocol** is an international effort to phase out CFCs, and has been successful in limiting ozone depletion.

Acid deposition occurs when certain air pollutants react with atmosphere to produce nitric and sulfuric acids. It can reach Earth as various forms of precipitation or as dry particles that later react to form acid. The precursors of acid deposition result from both natural sources, such as volcanoes and decaying vegetation, and **anthropogenic** (human) sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NOx) resulting from fossil fuel combustion. Acid deposition causes acidification of lakes and streams, contributes to the damage of trees and many sensitive forest soils. In addition, acid deposition accelerates the decay of building materials and paints, contributes to the corrosion of metals and damages human health. However, the severity of acid deposition has declined due ot regulations and technologies that limit air pollution.

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21: CLIMATE CHANGE

Chapter Hook

The iconic Grand Canal of Venice, Italy, doesn't need high quality instruments to note effects of climate change. The Grand Canal was built in a way that the water levels are directly correlated with the sea level. As such, the steps leading into the canal have become rulers for sea level changes over the hundreds of years of their existence. The last step leading into the canal directly reflected the sea level at the time of creation and currently, the water level is 3 feet above this. In the last quarter century, sea levels have been rising much faster than previously measured. This puts Venice in a difficult position moving into a future where scientists predict the sea level to continue to rise, estimating that the city will be underwater by 2100, along with many other coastal cities. Unfortunately, rising seas are only one of the many predicted outcomes of global climate change.

Figure $21.a$: Flooding in Venice, Italy. Image by WorldIslandInfo.com in Wikimedia Commons (CC-BY2.0).

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. **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.

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. Long-range weather forecasts are available but can be unreliable.

To better understand the difference between climate and weather, imagine that you are planning an outdoor event in northern Wisconsin. You would be thinking about *climate* when you plan the event in the summer rather than the winter because you have long-term knowledge that any given Saturday in the months of May to August would be a better choice for an outdoor event in Wisconsin than any given Saturday in January. However, you cannot determine the specific day that the event should be held on because it is difficult to accurately predict the weather on a specific day. Climate can be considered "average" weather.

21.1: The Greenhouse Effect and Climate Change
21.2: Data Dive- Flooding in Venice Italy
21.3: Review

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21.1: The Greenhouse Effect and 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, human activities, especially our combustion of fossil fuels, explains the current warming (figure $21.1.a$). 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.

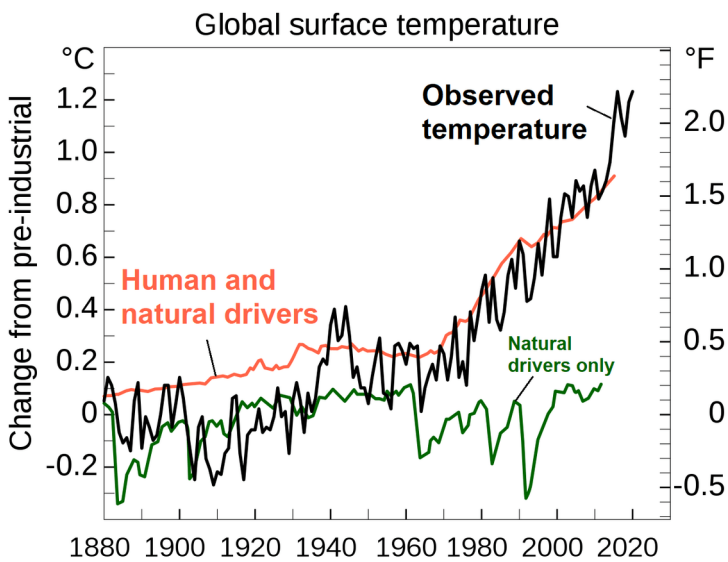

Figure $21.1.a$: This graph shows the predicted temperatures from two climate models and observed temperatures from 1880 to 2020. The first model considered only natural factors that could influence temperature and is represented by the green line (bottom). It shows some fluctuations in temperature by no overall increase or decrease. The second model considered both human and natural factors and is represented by the orange line (top). It shows an overall increase in temperature. Actual observations (black, jagged line; middle) more closely match the second model. Overall, temperature has increased about 1.2 degrees Celsius (2.1 degrees Fahrenheit) since pre-industrial times. Image relabeled from Efbrazil (CC-BY-SA).

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 video below made for kids, but provides a clear and simple introduction to the greenhouse effect.

YouTube Video

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

View this YouTube Video online

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 $21.1.b$). 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 -18° C without naturally-occurring GHGs.

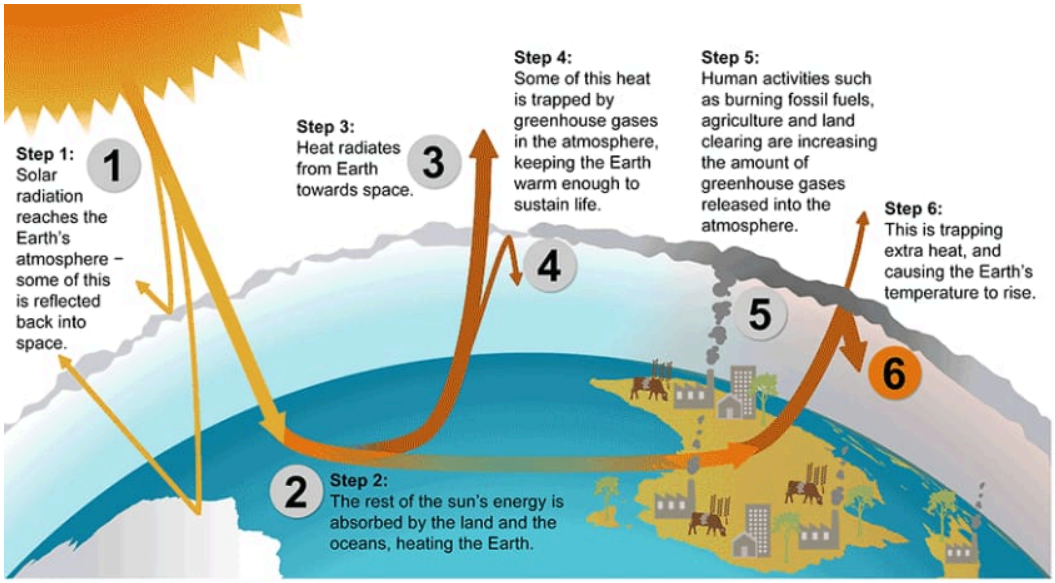

Figure $21.1.b$: The enhanced greenhouse effect. Step 1: Some solar radiation reaches the Earth's surface, and some is reflected back into space. Step 2: The rest of the sun's energy is absorbed by the land and the oceans, heating the Earth. Step 3: Heat radiates from Earth towards space. Step 4: Some of the heat is trapped by greenhouse gases in the atmosphere, warming the Earth. Step 5: Human activities such as burning fossil fuels, agriculture, and land clearing have increased the concentrations of greenhouse gases in the atmosphere. Step 6: This is trapping extra heat, causing the Earth's temperature to rise.

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.

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 409.8 ppm in 2019 (figure $21.1.c$). 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 (figure $21.1.d - f$). Human activities currently release over 30 billion tons of CO_2 into the atmosphere every year. While some volcanic eruptions released large quantities of CO_2 in the distant past, the U.S. Geological Survey (USGS) reports that human activities now emit more than 135 times as much CO_2 as volcanoes each year. This human-caused build-up of CO_2 in the atmosphere is like a tub filling with water, where more water flows from the faucet than the drain can take away.

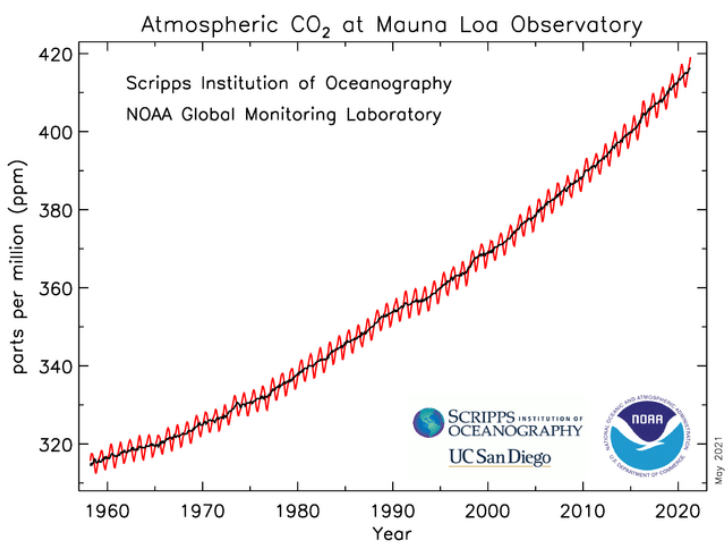

Figure $21.1.c$: Monthly mean carbon dioxide concentration in parts per million (ppm) measured at Mauna Loa Observatory, Hawaii. The carbon dioxide data on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere. The fluctuating red line represents the monthly mean values, centered on the middle of each month. Carbon dioxide concentrations dip every summer due to increased photosynthesis. The smoother black line represents the same, after correction for the average seasonal cycle. Image and caption (modified) by NOAA (public domain).

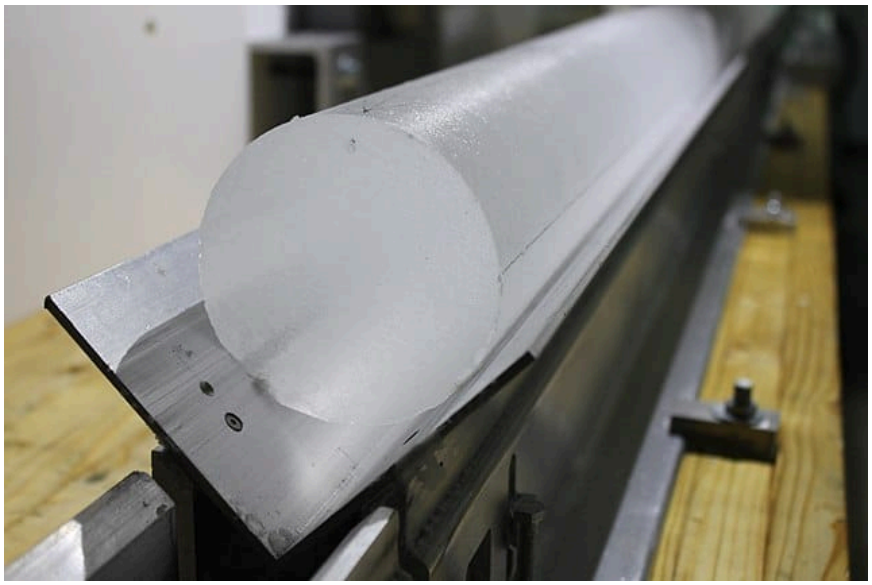

Figure 21.1.d: The EastGRIP ice core, which was drilled from the Greenland Ice Sheet. You can read more here. Image by Helle Astrid Kjær (CC-BY).

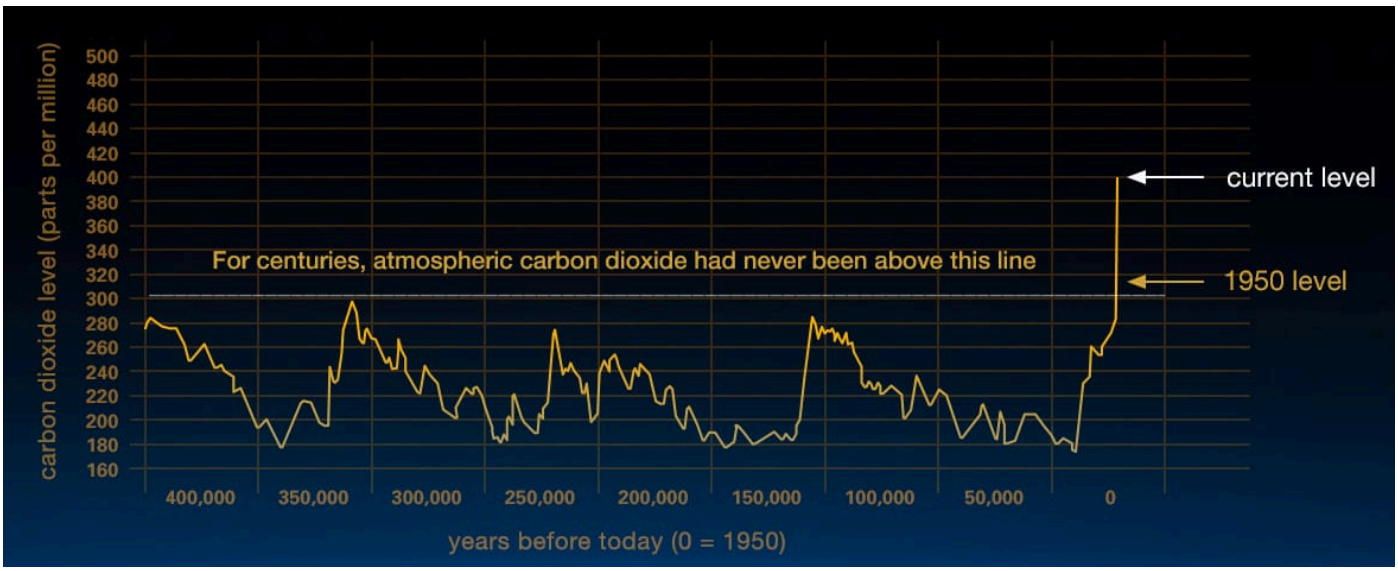

Figure 21.1.e: This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO2 has increased since the Industrial Revolution. On the x-axis are the years before today (0 = 1950). It begins 400,000 years prior to 1950. On the y-axis is the carbon dioxide level in parts per million. Carbon dioxide levels have fluctuated over the years, but they never exceeded 300 parts per million until 1950. In 2018, carbon dioxide levels reached 409.8 ppm. (This graph is a few years old and shows the current CO_2 level at 400 ppm; Credit: Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO2 record.)

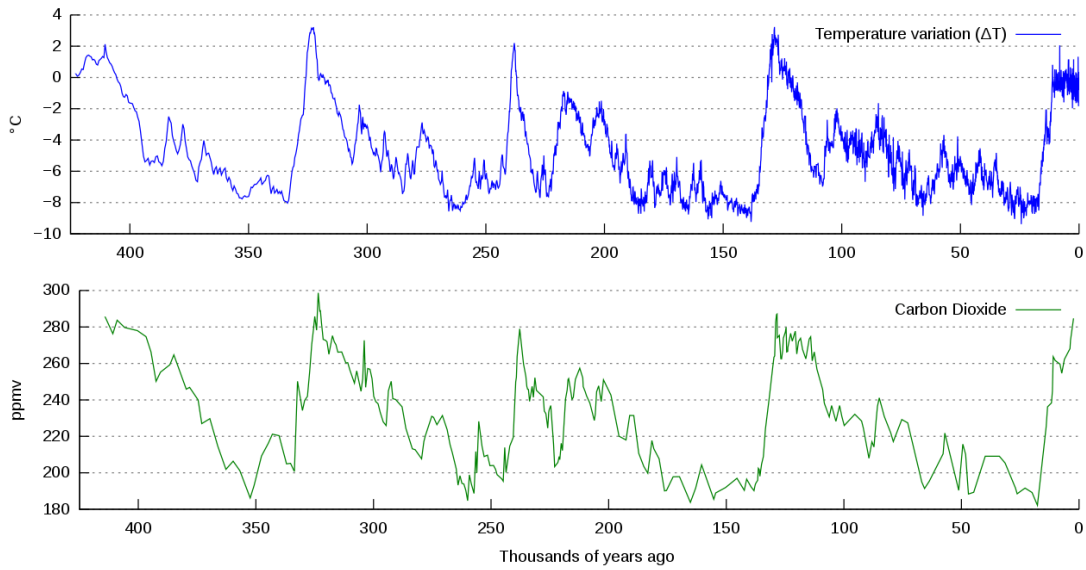

Figure 21.1.f: Graph of change in temperature in degrees Celsius (top, blue line) and carbon dioxide concentration in parts per million by volume (bottom, green line) measured from the Vostok, Antarctica ice core. These have been associated for over 400,000 years. As carbon dioxide concentration increased, so did temperature. As carbon dioxide concentration decreased, so did temperature. These data were collected in 1999. Since then, carbon dioxide concentrations have increased to 409.8 ppm (2019 average). Image and caption (modified) by NOAA/Autopilot (CC-BY-SA)

Other Greenhouse Gasses

Although this concentration is far less than that of CO_2, **methane** (CH_4) is 28 times as potent a greenhouse gas. Methane is produced when bacteria break down organic matter under anaerobic conditions and can be released due to natural or anthropogenic processes. Anaerobic conditions can happen when organic matter is trapped underwater (such as in rice paddies) or in the intestines of herbivores. Anthropogenic causes now account for 60% of total methane release. Examples include agriculture, fossil fuel extraction and transport, mining, landfill use, and burning of forests. Specifically, raising cattle releases methane due to fermentation in their rumens produces methane that is expelled from their GI tract. Methane is more abundant in Earth's atmosphere now than at any time in at least the past 650,000 years, and CH_4 concentrations increased sharply during most of the 20th century. They are now more than two and-a-half times pre-industrial levels (1.9 ppm), but the rate of increase has slowed considerably in recent decades.

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.

Current Status of Global Climate Change and Future Changes

Greenhouse gas concentrations in the atmosphere will continue to increase unless the billions of tons of anthropogenic emissions each year decrease substantially. Increased concentrations are expected to do the following:

- Increase Earth's average temperature (figure $21.1.g$),
- Influence the patterns and amounts of precipitation,
- Reduce ice and snow cover, as well as permafrost,
- Raise sea level (figure $21.1.h$),
- Increase the acidity of the oceans.

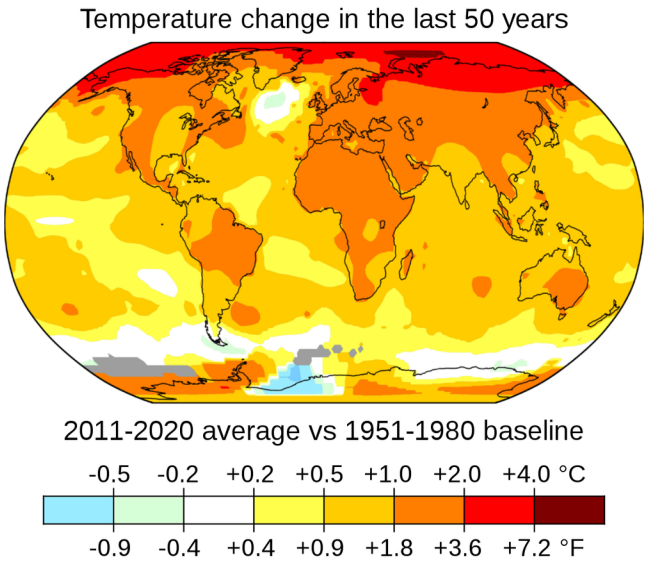

Figure $21.1.g$: Temperature increases have been most pronounced in northern latitudes and over land masses. The colors represent the temperature difference between the 2011-2020 average and the 1951-1980 baseline, with warmer colors (yellow, orange, red) representing increases, and cool colors (green, blue) representing decreases. The image uses longer term averages of at least a decade to smooth out climate variability due to factors such as El Niño. Grey areas in the image have insufficient data for rendering. Image and caption (modified) from NASA's Scientific Visualization Studio/Eric Fisk (public domain).

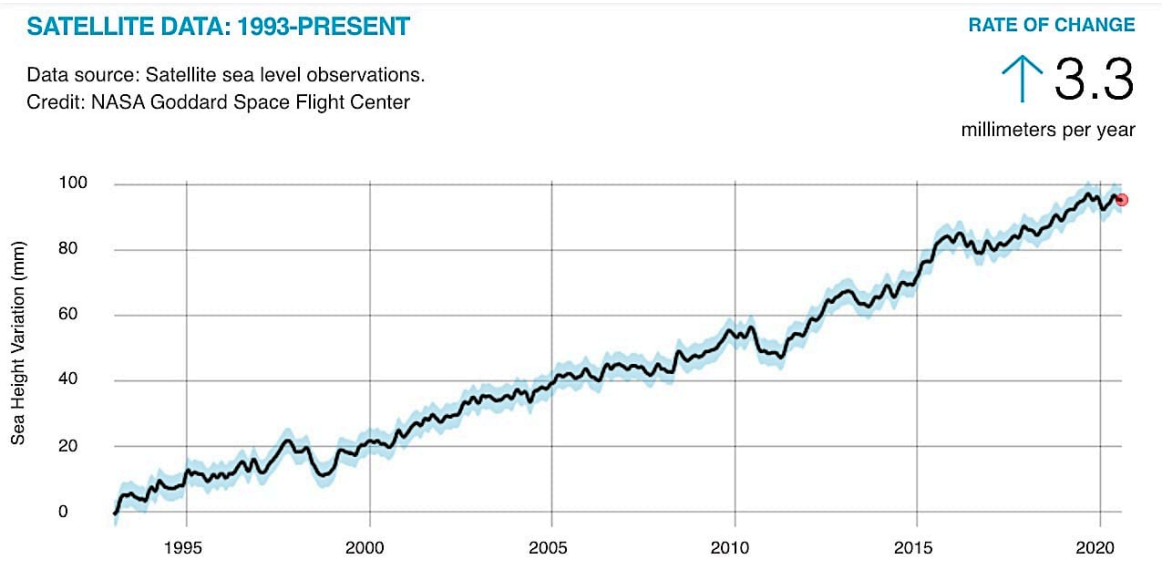

Figure $21.1.h$**:** Sea height variation (mm) over time. Sea height has increased about 3.3 millimeters per year on average since 1993. Data is from satellite sea level observations by the NASA Goddard Space Flight Center. Image by NASA (public domain).

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:

- 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 (figure $21.1.i$). 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

Figure $21.1.i$: The United States government paid for the residents of Isle De Jean Charles, an island south of Louisiana (that is also part of Louisiana), to relocate when it became inhabitable due to sea level rise. Image by Karen Apricot (CC-BY-SA).

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.

Mismatched Interactions

Climate change also affects phenology, 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 earlier 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.

Likewise, migratory birds rely on daylength cues, which are not influenced by climate change. Their insect food sources, however, emerge earlier in the year in response to warmer temperatures. As a result, climate change decreases food availability for migratory bird species.

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 does not only increase the spread of diseases in humans. Rising temperatures are associated with greater amphibian mortality due to chytridiomycosis (see Invasive Species). Similarly, warmer temperatures have exacerbated bark beetle infestations of coniferous trees, such as pine an spruce.

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 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.

NASA. 2018. Global Climate Change: Vital Signs of the Planet. 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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21.2: Data Dive- Flooding in Venice Italy

Overview

Historically, Venice Italy has a history of flooding that is caused from a multitude of both natural and human caused phenomena. Currently, these issues are being exacerbated by sea level changes as a result of climate change. As such, the City of Venice has been carefully tracking frequency of flooding through the years. The graph below represents the frequency of water level was above 110cm per 10-year period:

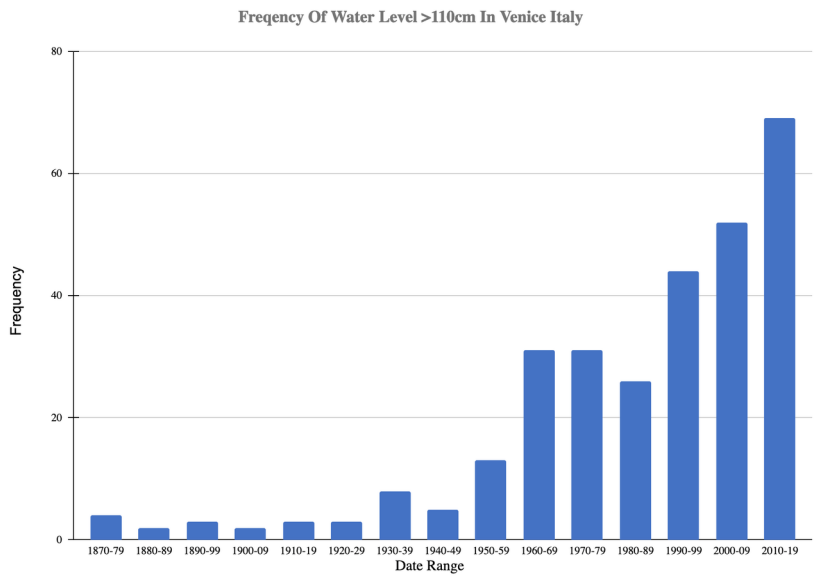

Figure $21.2.a$: Frequency of flooding exceeding 110cm in Venice Italy. Graph by Rachel Schleiger (CC-BY-NC) modified from data published by the City of Venice.

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph?
3. What are the results of this graph illustrating about flooding in Venice?
4. How can other coastal cities around the world learn from what patterns are emerging in this graph?
5. Provide a brief reflection for how these results make you feel and what they make you think about.

Raw Data For Above Graph(s)

Table $21.2.a$**:** Raw data for the frequency of flooding exceeding 110cm in Venice Italy. Graph by Rachel Schleiger (CC-BY-NC) modified from data published by the City of Venice.

Ten Year Interval	Frequency
1870-79	4
1880-89	2
1890-99	3
1900-09	2
1910-19	3

Ten Year Interval	Frequency
1920-29	3
1930-39	8
1940-49	5
1950-59	13
1960-69	31
1970-79	31
1980-89	26
1990-99	44
2000-09	52
2010-19	69

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21.3: Review

Summary

After completing this chapter you should be able to...

- Define global climate change.
- Summarize the effects of the Industrial Revolution on global atmospheric carbon dioxide concentration.
- Describe three natural factors affecting long-term global climate.
- List two or more greenhouse gases and describe their role in the greenhouse effect.

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.

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22: SUSTAINABILITY

Connecting Environmental Science to Sustainability

Both environmental science and sustainability originated out of necessity due to past and current issues to find solutions for the now and the future. As such, there are many parallels to these subjects basic objectives. However, environmental science focuses on environmental/ecological solutions (as outlined in this book), whereas sustainability focuses on environmental/ecological, social, and economic goals. That's even more interdisciplinary, and thus complex, than environmental science! As such, this chapter will solely introduce essential concepts of sustainability and will not be entirely comprehensive.

Figure $22.a$**:** Example goals of sustainability. Image by Wikimedia Commons (CC-BY-SA4.0)

22.1: Introduction to Sustainability

22.2: History of Sustainability

22.3: Environmental Ethics

22.3.1: Environmental Justice and Indigenous Struggles

22.3.2: Perspectives of the Environment

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22.5: Sustainable Cities

22.6: Sustainability and the Future

22.7: Data Dive- Sustainable Investments

22.8: Review

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Thumbnail - "Sustainability diagram" Is in the Public Domain

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22.1: Introduction to Sustainability

Chapter Hook

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 their dedication to keeping their carbon dioxide emissions low. Figure $22.1.a$ below shows the difference in emissions for the United States and Switzerland:

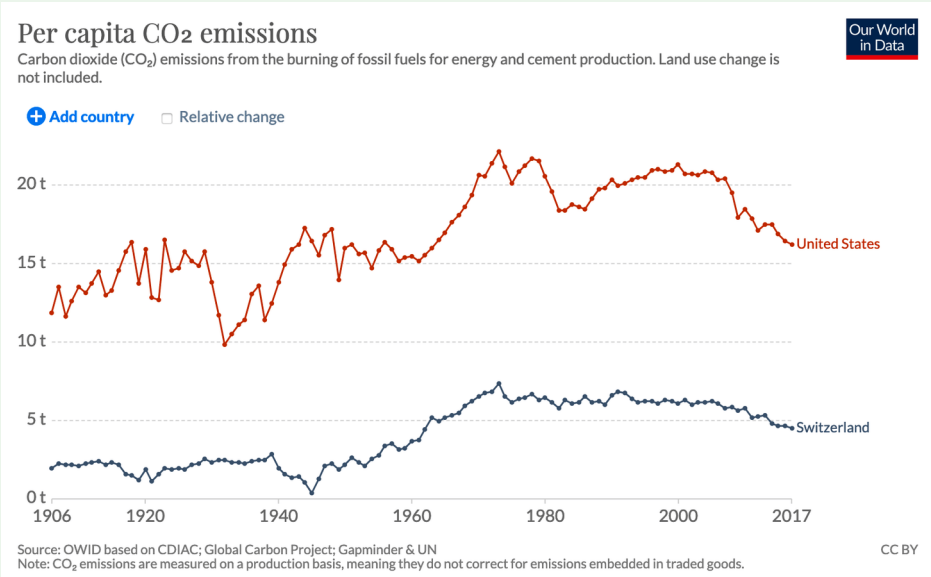

Figure $22.1.a$: Per capita emissions of carbon dioxide between the United States and Switzerland. Graph by Our World in Data (CC-BY4.0)

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, competences and other attributes embodied in individuals that are relevant to economic activity.
- Environmental aspects recognize the diversity and interdependence within living systems, the goods and services produced by the world's ecosystems, and the impacts of human wastes.
- Social/Socio-political refers to interactions between institutions/firms and people, functions expressive of human values, aspirations and well-being, ethical issues, and decision-making that depends upon collective action.

The intersection of social and economic elements can form the basis of social "equitability". In the sense of enlightened management, "viability" is formed through consideration of economic and environmental interests. Between environment and social elements lies "bearability," the recognition that the functioning of societies is dependent on environmental resources and services. At the intersection of all three of these lies sustainability (figure $22.1.b$).

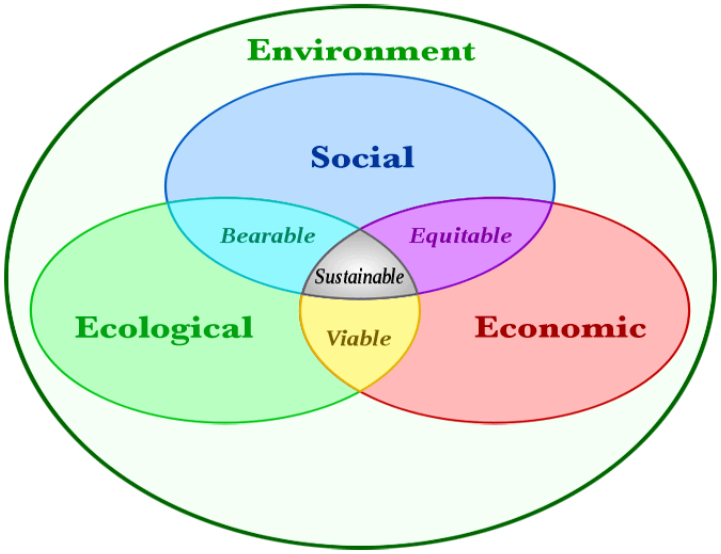

Figure $22.1.b$**:** Venn diagram of defining the components of sustainability. Image by Andrew, Sunray, based on "File:Sustainable development.svg" by Johann Dréo in Wikimedia Commons (CC-BY-SA4.0)

The three main elements of the sustainability paradigm are thought of as equally important, however, tradeoffs occur depending on the local/global objective. For example, in some instances it may be deemed necessary to degrade a particular ecosystem in order to facilitate commerce, or food production, or housing. In reality, the extent to which tradeoffs can be made before irreversible damage results is not always known, and in any case there are definite limits on how much substitution among the three elements is wise (to date, humans have treated economic development as the dominant one of the three). This has led to the notion of strong sustainability, where tradeoffs among natural, human, and social capital are not allowed or are very restricted, and weak sustainability, where tradeoffs are unrestricted or have few limits. Whether or not one follows the strong or weak form of sustainability, it is important to understand that while economic and social systems are human creations, the environment is not. Rather, a functioning environment underpins both society and the economy.

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22.2: History of Sustainability

Taking The Long View: Sustainability an Evolutionary and Ecological Perspective

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

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

There are three primary reasons for this:

1. Mechanization of both industry and agriculture in the last century resulted in vastly improved labor productivity which enabled the creation of goods and services. Since then, scientific advance and technological innovation — powered by ever-increasing inputs of fossil fuels and their derivatives — have revolutionized every industry and created many new ones. The subsequent development of western consumer culture, and the satisfaction of the accompanying disposable mentality, has generated material flows of an unprecedented scale. The Wuppertal Institute estimates that humans are now responsible for moving greater amounts of matter across the planet than all natural occurrences (earthquakes, storms, etc.) put together.
2. The sheer size of the human population is unprecedented. Every passing year adds another 90 million people to the planet. Even though the environmental impact varies significantly between countries (and within them), the exponential growth in human numbers, coupled with rising material expectations in a world of limited resources, has catapulted the issue of distribution to prominence. Global inequalities in resource consumption and purchasing power mark the clearest dividing line between the haves and the have-nots. It has become apparent that present patterns of production and consumption are unsustainable for a global population that is projected to reach between 12 billion by the year 2050. If ecological crises and rising social conflict are to be countered, the present rates of over-consumption by a rich minority, and under-consumption by a large majority, will have to be brought into balance.
3. It is not only the rate and the scale of change but the nature of that change that is unprecedented. Human inventiveness has introduced chemicals and materials into the environment which either do not occur naturally at all, or do not occur in the ratios in which we have introduced them. These persistent chemical pollutants are believed to be causing alterations in the environment, the effects of which are only slowly manifesting themselves, and the full scale of which is beyond calculation. CFCs and PCBs are but two examples of the approximately 100,000 chemicals currently in global circulation. (Between 500 and 1,000 new chemicals are being added to this list annually.) The majority of these chemicals have not been tested for their toxicity on humans and other life forms, let alone tested for their effects in combination with other chemicals. These issues are now the subject of special UN and other intergovernmental working groups.

The Evolution of Sustainability Itself

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

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

Figure $22.2.a$**:** Cover of Our Common Future. Image by Sigurður Kaiser in Wikimedia Commons (CC-BY-SA4.0)

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.

Precautionary Principle

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

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22.3: ENVIRONMENTAL ETHICS

Introduction

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 the 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 persons values extend outside of themselves (Figure 7.2a). 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).

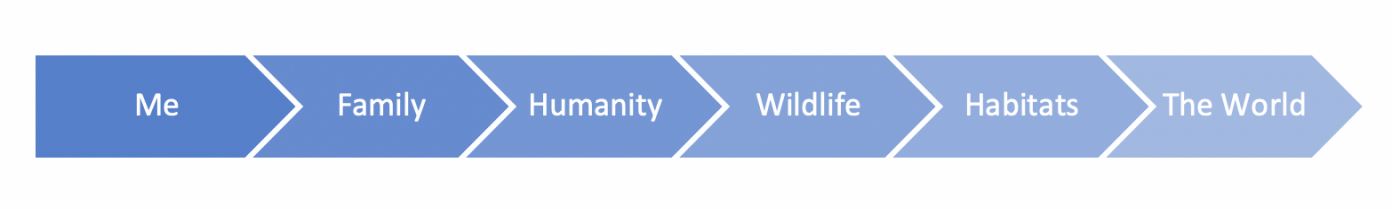

Figure $22.3.a$**:** Scope of consideration for moral extensionism. Image by Rachel Schleiger (CC-BY-NC).

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- Topic hierarchy

22.3.1: Environmental Justice and Indigenous Struggles

22.3.2: Perspectives of the Environment

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22.3.1: Environmental Justice and Indigenous Struggles

Environmental Equity

Environmental equity describes a country, or world, in which no single group or community faces disadvantages in dealing with environmental hazards, disasters, or pollution. 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.

Global Consumption Inequality - 24% of the global population (mostly in the high income countries) accounts for...

- 92% Cars
- 70% Carbon dioxide emissions
- 86% Copper and aluminum
- 81% Paper
- 80% Iron and steel
- 48% Cereal crops
- 60% Artificial fertilizer

If the remaining three-quarters were to exercise their right to grow to the level of the rich minority it would result in ecological devastation. So far, global income inequalities and lack of purchasing power have prevented poorer countries from reaching the standard of living (and also resource consumption/waste emission) of the industrialized countries. Countries such as China, Brazil, India, and Malaysia are, however, catching up fast. In such a situation, global consumption of resources and energy needs to be drastically reduced to a point where it can be repeated by future generations. But who will do the reducing? Poorer nations want to produce and consume more. Yet so do richer countries: their economies demand ever greater consumption-based expansion. Such stalemates have prevented any meaningful progress towards equitable and sustainable resource distribution at the international level. These issue of fairness and distributional justice remain unresolved.

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.

In Flint Michigan, the city decided to save money by drawing water for residents from the Flint River in 2014. Residents complained about the taste, smell, and color of the water. A couple of scientific studies determined that there was a failure to apply corrosion inhibitors to the water, resulting in lead from aging pipes to leach into the water supply, exposing around 100,000 residents to elevated lead levels. Although the city switched back to it's original water source, the damage was already done. Not only did this crisis expose so many to lead, especially concerning for children, but also most pipes needed to be replaced as they were no longer safe to use (Figure a). In 2017 a settlement was reached to replace all the pipes, a $87 million project. However, as of Jan 2021 this project is only just now approaching completion. Citywide lead levels have tested within the safe range for consumption, though houses considered high risk do continue to show elevated levels.

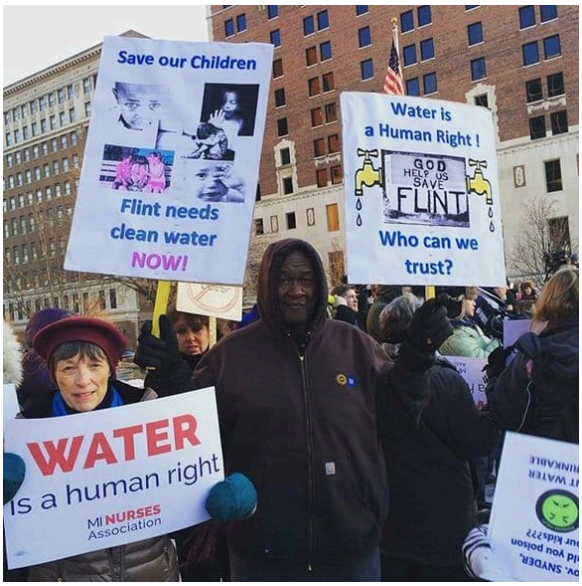

Figure $22.3.1.a$**:** Flint residents trying to bring awareness of Flint Water Crisis through peaceful demonstration. Image by Shannon Nobles in Wikimedia Commons (CC-BY-SA-4.0).

During the 1980's marginalized groups protested that hazardous waste sites were preferentially sited in their 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. **Environmental racism** occurs when marginalized groups and people of color are disproportionately exposed to environmental hazards.. Confounding this issue, 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 financially constrained to live in these areas.

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 wastes to plague this planet. Unfortunately, we live in a world with rampant pollution, dumping of hazardous wastes, and people with "living for the now" attitudes. Our industrialized society has necessarily produced wastes 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 marginalized and low income groups.

Indigenous People

Since the end of the 15th century, much of the world has been claimed and colonized by established nations. Invariably, these conquered frontiers were home to people indigenous to those regions. Some were wiped out or assimilated by the invaders, while others survived while trying to maintain their unique cultures and way of life. The United Nations officially classifies **indigenous people** as those "having an historical continuity with pre-invasion and pre-colonial societies," and "consider themselves distinct from other sectors of the societies now prevailing in those territories or parts of them." Furthermore, indigenous people are "determined to preserve, develop and transmit to future generations, their ancestral territories, and their ethnic identity, as the basis of their continued existence as peoples in accordance with their own cultural patterns, social institutions and legal systems."

A few of the many groups of indigenous people around the world are: the many tribes of Native Americans (i.e., Navajo, Sioux) in the contiguous 48 states, the Inuit of the arctic region from Siberia to Canada, the rainforest tribes in Brazil, and the Ainu of northern Japan.

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

Despite the lofty U.N. goals, the rights and feelings of indigenous people are often ignored or minimized, even by supposedly culturally sensitive developed countries. In the United States many of those in the federal government are pushing to exploit oil resources in the Arctic National Wildlife Refuge on the northern coast of Alaska. The "Gwich'in," an indigenous people who rely culturally and spiritually on the herds of caribou that live in the region, claim that drilling in the region would devastate their way of life (Figure b). 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 22.3.1.b: Bernadette Demietieff speaking in support of protect the Arctic to protect Gwich'in land from oil drilling, Alaska, c. 2019. Image by: Deb Haaland in Wikimedia Commons (CC-BY-SA-4.0).

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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22.3.2: Perspectives of the Environment

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 are 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 sand 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)

Case Study: Hetch Hetchy

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 $22.3.2.a$**:** Aerial view of Hetch Hetchy Reservoir, California, USA. Image by Ken Lund in Wikimedia Commons (CC-BY-SA)

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

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

> "As to my attitude regarding the proposed use of Hetch Hetchy by the city of San Francisco...I am fully persuaded that... the injury...by substituting a lake for the present swampy floor of the valley...is altogether unimportant compared

with the benefits to be derived from it's use as a reservoir.

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

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

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

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

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22.4: 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 $22.4.a$**:** 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 $22.4.b$**:** 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

Year	Policy/Society/Organization Conception
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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22.5: Sustainable Cities

Introduction

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? While attempting to envision the "sustainable city" we must discern what factors will influence its shape and form in the future.

So what is the major hindrance for designing/updating for a "sustainable city"?

Sprawl: The outward expansion of human populations (typically in low-density residential and commercial development) into the outer edges of cities/towns.

As sprawl expands, it eats at natural and agricultural lands and isolates people. People have to travel further and further to go to work, the grocery store, a hospital, etcetera. What this means is that cities/towns have to find solutions to moving water, waste, power, services, road development/upkeep, etcetera to these communities. As such, there are chronic issues with sprawl on both sides that make opportunity and progress difficult due to economic constraints.

It's important to note that sprawl can happen at different scales:

- **Low-density sprawl:** Small 1-2 story buildings in high densities. Low-density sprawl can be further distinguished by income as neighborhoods tend to be segregated by this. (Ex: North America)
- **High-density sprawl:** High rise buildings in high densities (Ex: China)

Figure 22.5.a: Left - High density sprawl in Shanghai China by John Patrick Robichaud in Wikimedia Commons (CC-BY), Right - Low density sprawl in North America by Pixnio (Public Domain).

So what can be done to design/update and move towards “sustainable cities”?

- **Mixed use development:** Lends residential, commercial, cultural, institutional, or industrial uses, where those functions are physically and functionally integrated, and that provides pedestrian connections. Making cities walkable!
- **Geographic equity:** Circulation system defined by ratios of how people move. This means more bikes, walking, public transportation (in many forms) and not cars. Equitability of the streets!
- **Preserve:** Preserve land, culture, and biodiversity as much as possible.
- **Mix**: Mix incomes, cultures, green spaces, public transport options, etcetera as much as possible. Allow people to connect and become neighbors not strangers.
- **Focus:** Match density of a community to meet transit/service needs.

Video 22.5.a**:** Perspectives: Peter Calthrope describes 7 principles for building better cities.

YouTube Video

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22.6: Sustainability and the Future

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 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.

Common Cause and Sustainability

Common cause: Brings about change in all people/interest groups/world leaders because of common goals. Below are a list of sustainability goals across the sustainability paradigm. Most, if not all, are common cause goals for the now, and into the future.

Society

- No poverty
- Zero hunger
- Good health
- Quality education
- Gender equality
- Peace, justice, and strong institutions
- Clean water and sanitation
- Reduced inequalities

Environment

- Terrestrial life/habitats conservation and restoration
- Oceanic life/habitats conservation and restoration
- Climate action
- Reduced waste/pollution

Economy

- Affordable and clean energy
- Decent work and economic growth
- Industry, innovation, and infrastructure
- Responsible consumption and production

- Sustainable cities and communities
- Partnerships locally and globally

Sustainable Living

Sustainable living describes a lifestyle that attempts to reduce/eliminate an individuals (or societies) 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 for local concerns/needs versus global concerns/needs
- Sharing knowledge with their community (all ages)

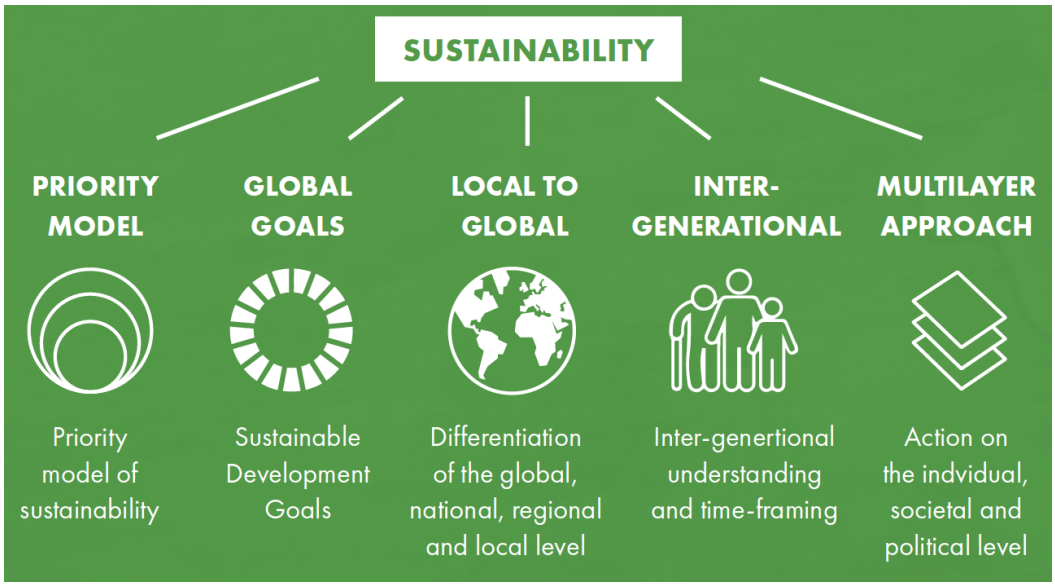

Figure $22.6.a$**:** Considerations for sustainable living goals. Image by Sustainability Week Switzerland in Wikimedia Commons (CC-BY-SA)

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 that entire burden does not lie with just one individuals control (see figure below). It takes a multi-layerd approach to appropriately take action at the individual, societal, and political levels (see figure above).

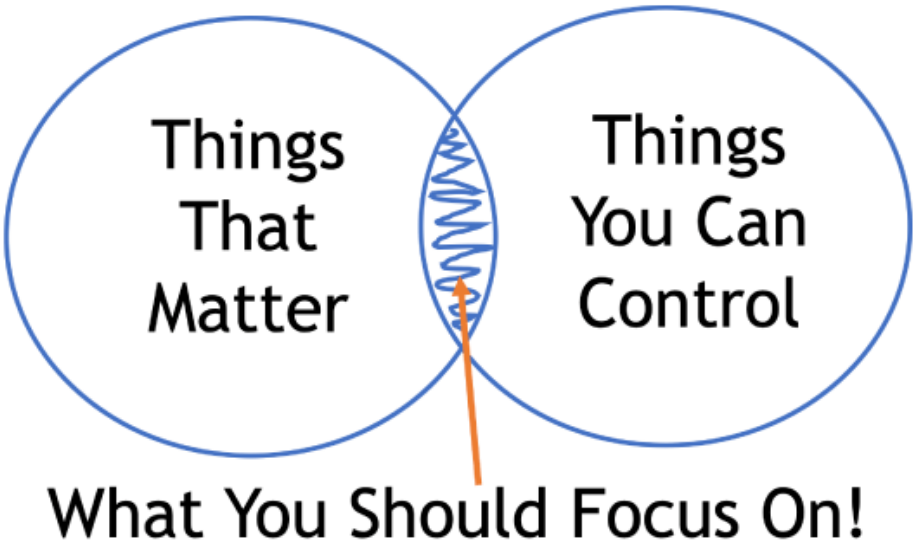

Figure $22.6.b$**:** Focus for individual sustainability lifestyle goals. Image by Rachel Schleiger (CC-BY-NC)

The Bionic World

This book will conclude by stating a huge myth held by most of today's society, the myth of the **Bionic World**. It is the belief that science and technology will solve the pressing issues of human's impact on this earth. If society follows this logic, we have no tough choices to make about how we view and treat our surroundings, and decisions can be put off until the economic markets demand or justify a solution. Society can hope to be right.... However, until supporting evidence emerges that humanity can solve all their own problems with the ever shrinking timeline to do so, then we need to start making tough choices to ensure an equitable and sustainable future.

Figure $22.6.c$**:** Robot arm holding up the Earth. Image by Pixabay (Public Domain)

Video $22.6.a$**:** Perspectives: Michael Green discusses sustainability goals and what we can do moving forward (Videos from 2015 and 2018)

YouTube Video

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22.7: Data Dive- Sustainable Investments

Overview

Climate change is the major focus of conversation across many different disciplines and interest groups. With a huge array of global sustainability challenges both now and in the future, investors are starting to re-evaluate where they want to spend their money. Today, sustainable investing is increasing exponentially! The graph below displays the global growth in sustainable investments between 2012 and 2018:

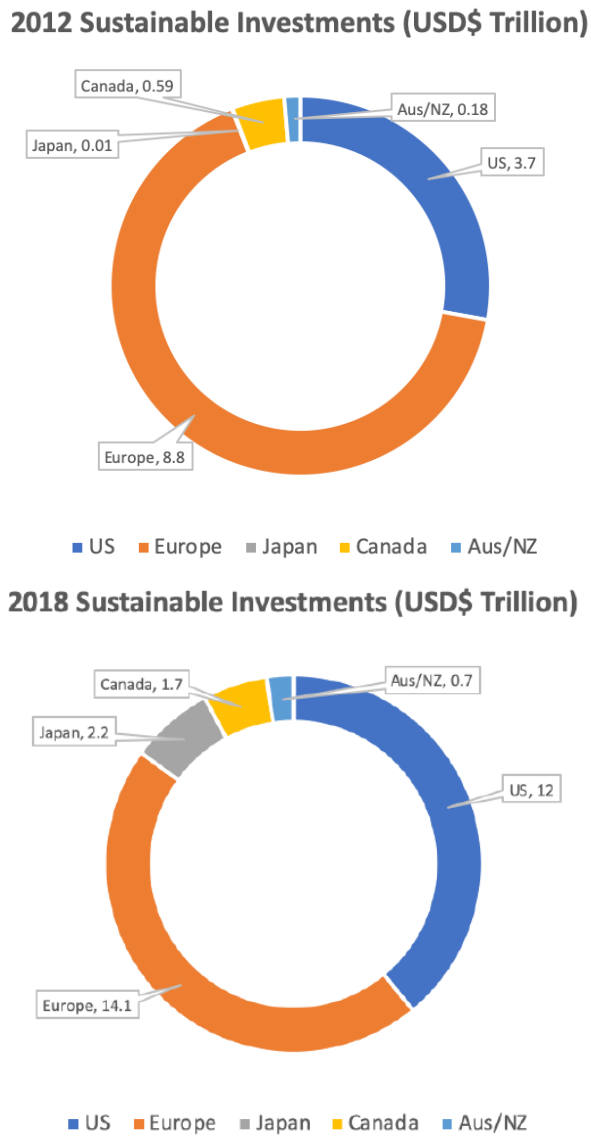

Figure 22.7.a: 2012 and 2018 global sustainable investments. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Global Sustainable Investment Alliance 2019.

Questions

1. What kind of graphs are these?
2. What major differences are there between the 2012 graph and the 2018 graph?

3. Which country(ies) is the major leader for sustainable investments?
4. Are there any countries/regions that are not represented on the graph that you would have predicted would be there?
5. Is there anything that surprises you about the results displayed in these graphs? Explain your answer.

Raw Data From Above Graph(s)

Table $22.7.a$**:** Raw data from 2012 and 2018 global sustainable investments. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Global Sustainable Investment Alliance 2019.

Country/Continent	2012 Investments (USD$ Trillion)	2018 Investments (USD$ Trillion)
United States	3.7	12
Europe	8.8	14.1
Japan	0.01	2.2
Canada	0.59	1.7
Australia/New Zealand	0.18	0.7

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22.8: Review

Summary

After completing this chapter you should be able to...

- Define sustainability and the sustainability paradigm
- Describe the historic events that lead to the sustainability paradigm
- Describe how ethics and moral extensionism connect to sustainability
- Understand that true sustainability promotes environmental equity and justice, thus eliminating environmental racism
- Describe the evolution of ethics leading to the modern environmental ethic
- Understand how environmental policy has changed based on movements and need in the US
- Define what sustainable cities are
- Describe how sprawl is a hindrance to sustainable cities
- Describe how sustainable lifestyle choices influence sustainability
- Acknowledge that the Bionic World is a myth

Sustainability is focused on meeting current needs without compromising the future generations to meet theirs. Sustainability is a paradigm created out of necessity from our past negligence to society, ecology, and economy (the three main components of sustainability).

Ethics plays a large role in addressing current and future sustainability goals necessitated from historic action/inaction. This is especially true for matters of **environmental justice and racism**, in addition to **environmental policies** and movements.

Sustainable cities are also discussed to address the large-scale sustainability concerns of how humanity lives. **Sprawl** is the biggest hindrance for creating the sustainable city. There are two main types of sprawl, **low-density** and **high-density**, that can be observed in many differently populated city layouts.

The **ecological footprint** is a tool to help illustrate the imbalance between lifestyles and behaviors and what is ecologically sustainable. In order to decrease ecological footprints, in addition to environmental injustices, sustainability promotes **common cause** sustainability goals. These emphasize that most goals humanity have are the same, and that these should be what both motivate and unite us as we move towards an uncertain future. In addition, humanity should also consider how we are approaching meeting these goals. The **myth of the bionic world** warns us not to make assumptions or take the easy way out. Only through tough decisions can we ensure an equitable and sustainable future.

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GLOSSARY

S

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