The Ecosphere and Environmental Issues

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Part V. Food and water for a growing population

Acknowledgements

Creation of this book was supported by the Virtual Library of Virginia (VIVA), grant number 087F19.

Please contact Sarah Sojka (ssojka@randolphcollege.edu) with any suggestions or errors in the book.

Introduction

This textbook is designed for introductory environmental studies and science students. The goal is to teach essential ecological concepts by linking them to key environmental issues. The hope is that students can easily understand how firm grounding in these concepts can help them appreciate and hopefully address the biggest environmental threats of our time. After an initial section on the nature of science and an overview of ecology, the textbook is divided into four sections, each addressing a key environmental concern: global climate change, eutrophication, biodiversity loss and food supply and security. After a brief introduction to the environmental concern, the book addresses ecological concepts relevant for understanding the issue. Each section wraps up with a return to the environmental concern and insight into how the ecological concepts learned can be applied to the environmental issue.

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PART I
GETTING STARTED

1. Nature of science

Before we start a textbook on ecology, we have to first describe what ecology is and why we should bother to learn it. Ecology is the scientific study of living organisms and their abiotic (non-living) and biotic (living) environments. We will look more closely at each part of this definition to describe ecology. In this chapter, we will explore the nature of science.

1.1 Ecology is a science, but what is science?

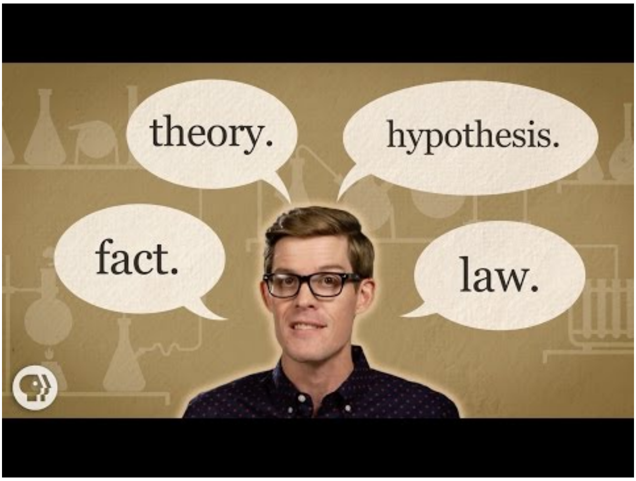
This is Grand Canyon of the Yellowstone in Yellowstone National Park. An objective statement about this would be: "The picture is of a waterfall." A subjective statement would be: "The picture is beautiful." An inference would be "The waterfall is there because of erosion."

Scientists seek to understand the fundamental principles that explain natural patterns and processes. Science is more than just a body of knowledge, science provides a means to evaluate and create new knowledge while minimizing bias [1].

Scientists use objective An observation that is completely free of bias, i.e. anyone and everyone would make the same observation. ">**objective** evidence over subjectiveAn observation which is influenced by the observer's personal bias.">**subjective** evidence, to reach sound and logical conclusions. An objectiveAn observation that is completely free of bias, i.e. anyone and everyone would make the same observation.">**objective** observationThe act of gathering new information from the senses or from a scientific instrument.">**observation** is without personal bias and the same by all individuals. Humans are biased by nature, so they cannot be completely objectiveAn observation that is completely free of bias, i.e. anyone and everyone would make the same observation.">**objective**; the goal is to be as unbiased as possible. A subjectiveAn observation which is influenced by the observer's personal bias.">**subjective** observationThe act of gathering new information from the senses or from a scientific instrument.">**observation** is based on a person's feelings and beliefs and is unique to that individual.

Another way scientists avoid bias is by using quantitativeAn observation which is based on numerical data. These observations are preferred because they can be used in calculations.">**quantitative** over qualitativeAn observation which is based on non-numerical data. While these types of observations are not preferred, they can still be useful.">**qualitative** measurements whenever possible. A quantitativeAn observation which is based on numerical data. These observations are preferred because they can be used in calculations.">quantitative measurement is expressed with a specific numerical value. qualitativeAn observation which is based on non-numerical data. While these types of observations are not preferred, they can still be useful.">Qualitative observations are general or relative descriptions. For example, describing a tree as tall or young is a qualitativeAn observation which is based on non-numerical data. While these types of observations are not preferred, they can still be useful.">qualitative observationThe act of gathering new information from the senses or from a scientific instrument.">observation. Measuring the height of the tree and using tree ring data to determine the tree age is quantitativeAn observation which is based on numerical data. These observations are preferred because they can be used in calculations.">quantitative. Numerical values are more precise than general descriptions, and they can be analyzed using statistical calculations. This is why quantitativeAn observation which is based on numerical data. These observations are preferred because they can be used in calculations.">quantitative measurements are much more useful to scientists than qualitativeAn observation which is based on non-numerical data. While these types of observations are not preferred, they can still be useful.">qualitative observations.

Falsifiability separates science from PseudoscienceA method of investigation the claims to be scientific, but does not hold up to full scientific scrutiny. Examples include astrology, paranormal studies, young-Earth creationism, and cryptozoology (i.e. the study of creatures like Bigfoot and the Loch Ness Monster).">**pseudoscience**. Scientists are wary of explanations of natural phenomena that discourage or avoid falsifiability. An explanation that cannot be tested or does not meet scientific standards is not considered science, but PseudoscienceA method of investigation the claims to be scientific, but does not hold up to full scientific scrutiny. Examples include astrology, paranormal studies, young-Earth creationism, and cryptozoology (i.e. the study of creatures like Bigfoot and the Loch Ness Monster).">pseudoscience. PseudoscienceA method of investigation the claims to be scientific, but does not hold up to full scientific scrutiny. Examples include astrology, paranormal studies, young-Earth creationism, and cryptozoology (i.e. the study of creatures like Bigfoot and the Loch Ness Monster).">Pseudoscience is a collection of ideas that may appear scientific but does not use the scientific methodThe idea in science that phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">**scientific method**. Astrology is an example of PseudoscienceA method of investigation the claims to be scientific, but does not hold up to full scientific scrutiny. Examples include astrology, paranormal studies, young-Earth creationism, and cryptozoology (i.e. the study of creatures like Bigfoot and the Loch Ness Monster).">pseudoscience. It is a belief systemAn interconnected set of parts that combine and make up a whole.">**system** that claims that the movement of celestial bodies influences human behavior. Astrologers rely on celestial observations, but their conclusions are not based on experimental evidence and their statements are not falsifiableThe idea that any claim in science can be proved wrong with proper evidence.">**falsifiable**. This is not to be confused with astronomy which is the scientific study of celestial bodies and the cosmos [2; 3]. Establishing truth in science is difficult because all scientific claims are falsifiableThe idea that any claim in science can be proved wrong with proper evidence.">falsifiable, which means any initial hypothesisA proposed explanation for an observation that can be tested.">**hypothesis** may be tested and proven false. A hypothesis a specific, testable explanation of how multiple variables and observations relate (for example, increased nitrogen in the soil will have increase the fruit production of tomatoes more than it will increase the fruit production of snap peas when fruit production is measured as the total mass of fruit). One common misconception is that if a hypothesis is supported, it becomes a theory. This is used to help distinguish between the typical use of "theory" in everyday conversation and overarching theories in science like gravity and evolution. A scientific **theory** is a broad explanation for how something in the world works based on observations and previous research. A hypothesis is much more specific. If repeated testing of hypotheses generated from the theory indicates that the theory is a good explanation for the phenomena, the theory gains acceptance, but the hypotheses do not become theories. Similarly, lots of hypotheses that have been confirmed can be pulled together to form a theory. A theory is always subject to revision or even rejection based on new evidence and testing of hypotheses generated from the theory or from competing theories. This meticulous scrutiny reveals weaknesses or flaws in a hypothesisA proposed explanation for an observation that can be tested.">hypothesis and is the strength that supports all scientific ideas and procedures. In fact, proving current ideas are wrong has been the shear forceComponent of the gravitational force which pushes material downslope.">driving force behind many scientific careers. Despite this, some theories explain such a wide range of phenomena and are so well-supported, that they can be considered overarching or fundamental theories. Examples include plate tectonics, evolution, and special relativity.



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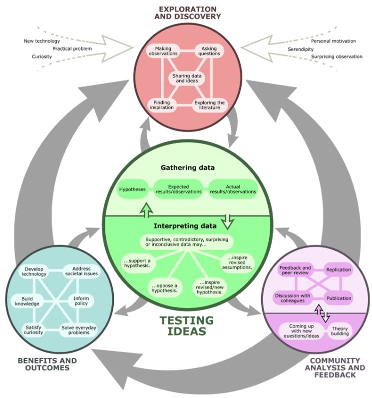
1.2 The Scientific Method

Modern science is based on the scientific methodThe idea in science that phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">scientific method, an iterative process in which scientists



This flowchart from the University of California Museum of Paleontology demonstrates a more complete view of the scientific method and demonstrates that the steps are not followed in a linear fashion. Image from "The real process of science" Understanding Science. University of California Museum of Paleontology. 14 July 2020 <https://undsci.berkeley.edu/article/0_0_0/howscienceworks_02>. Used with permission.

- Formulate a question or observe a problem (Exploration and discovery)
- Apply objectiveAn observation that is completely free of bias, i.e. anyone and everyone would make the same observation.">objective experimentation and observationThe act of gathering new information from the senses or from a scientific instrument.">observation (Gathering data)
- Analyze collected data and interpret results (Interpreting data)
- Submit findings to peer reviewA process where experts in a field review and comment on a newly-introduced work, typically a part of publication.">peer review and publication (Community analysis and feedback)

This has a long history in human thought but was first fully formed by Ibn al-Haytham over 1,000 years ago. At the forefront of the scientific methodThe idea in science that phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">scientific method are conclusions based on objectiveAn observation that is completely free of bias, i.e. anyone and everyone would make the same observation.">objective evidence, not opinion or hearsay [4]. The scientific methods is also not a linear path. Students often think that the purpose of scientific exploration is to "prove" a hypothesis. In fact, the goal of science is always to "test" the hypothesis and then to share the findings with the larger scientific community to help build our collective understanding of the world.

STEP ONE: FORMULATE A QUESTION OR OBSERVE A PROBLEM

The procedure begins with identifying a problem or research question, such as a phenomenon that is not well explained in the scientific community's collective knowledge. This step usually involves reviewing the scientific literature to understand previous studies that may be related to the question. This step can also be one of the most creative steps in the scientific method. Consider Alexander Fleming's discovery of penicillin. The story is often told that Fleming discovered penicillin by accident, which is partially true. Fleming was studying staphylococcal bacteria and left a petri dish sitting out while on vacation (some say it was supposed to be in the incubator, some reports say it was supposed to be thrown away). When he returned, he found that there were areas on the petri dish where the bacteria was dying. This was a chance observation, but Fleming's previous work on antimicrobial substances helped him understand the observation and develop and complete testing that led to the discovery of penicillin. The story of Alexander Fleming illustrates how knowledge of the field, previous research, chance, careful observation, and some creativity can all come together to help develop a research question and an approach to answering that question.

Once the problem or question is well defined, the scientist proposes a possible answer, a hypothesisA proposed explanation for an observation that can be tested.">hypothesis, before conducting an experimentA test of an idea in which new information can be gathered to either accept or reject a hypothesis.">**experiment** or fieldwork. This hypothesisA proposed explanation for an observation that can be tested.">hypothesis must be specific, falsifiableThe idea that any claim in science can be proved wrong with proper evidence.">falsifiable, and should be based on other scientific work. Most people have been taught at some point that a hypothesis is an "educated guess." This definition has some merit, in that a good hypothesis is based on an understanding of similar phenomena, previous experience, and education, but a hypothesis must be testable. A scientist's job is never to prove a hypothesis but to test the hypothesis.

STEP TWO: APPLY OBJECTIVE EXPERIMENTATION AND OBSERVATION

The next step is developing a way of testing the hypothesisA proposed explanation for an observation that can be tested.">hypothesis. More accurately, scientists often test a prediction based on the hypothesis. Scientists often use controlled experiments at this step, but computer models, analysis of existing data sets, and long-term observations can also be used to test the hypothesis. For example, one of the most impactful research projects in environmental science is the long-term record of atmospheric CO_2 concentrations from the Mauna Loa Observatory. The graph of this record, the Keeling Curve, demonstrated both that atmospheric CO_2 varies with a predictable seasonal pattern and that atmospheric CO_2 is increasing. Many people mistakenly think experiments are only done in a lab; however, an experimentA test of an idea in which new information can be gathered to either accept or reject a hypothesis.">experiment can consist of observing natural processes in the field. In some cases, scientists use natural experiments, like the recovery of a forest after a fire, or compare different ecosystems, such as examining the animal species living in an agricultural field vs a neighboring meadow. Regardless of how a scientist tests a hypothesis, it always includes the systematic gathering of objectiveAn observation that is completely free of bias, i.e. anyone and everyone would make the same observation.">objective data.

STEP THREE: ANALYZE COLLECTED DATA AND INTERPRET RESULTS

The objective data is interpreted to determine whether it contradicts or supports the hypothesisA proposed explanation for an observation that can be tested.">hypothesis. Data interpretation and analysis is a key step in the experimentation process. Scientists do not simply record their data, make a graph and finish. Scientists use their understanding of the field to determine what the data means. In scientific writing, scientists typically separate this interpretation step (the discussion) from the concrete data (the results) in the experiment. On occasion, scientists may need to revise their experimental approach. This is not done because the data is not supporting the hypothesis, but should only be done if the scientist discovers that the current experimental approach is not effective at testing the hypothesis and answering the research question.

STEP FOUR: SUBMIT FINDINGS TO PEER REVIEW AND PUBLICATION

Scientists share the results of their research by publishing articles in scientific journals, such as *Science* and *Nature*, and presenting at conferences. Reputable journals and publishing houses will not publish an experimental study until they have determined its methods are scientifically rigorous and the conclusions are supported by evidence. Before an article is published, it undergoes a rigorous peer reviewA process where experts in a field review and comment on a newly-introduced work, typically a part of publication.">peer review by scientific experts who scrutinize the methods, results, and discussion. Once an article is published, other scientists may attempt to replicate the results. This replication is necessary to confirm the reliability of the study's reported results. A hypothesisA proposed explanation for an observation that can be tested.">hypothesis that seemed compelling in one study might be proven false in studies conducted by other scientists. Scientific thinking requires that scientists revise their ideas in light of new evidence. New technology can be applied to published studies, which can aid in confirming or rejecting once-accepted ideas and/or hypothesisA proposed explanation for an observation that can be tested.">hypotheses. Scientific discovery is an ongoing process and a key element is that scientists present their work for scrutiny by others and for others to use for their own research.

This process seems straightforward and linear, but in fact, scientists repeat steps, loopback in the process, and get stuck all the time. The TED talk below gives a more accurate description of how science is done.

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Another key aspect of the scientific process is the impact and benefits of the research. Sometimes, research impacts policy or human behavior. Sometimes it leads to a new medication. Sometimes, it leads to more research which then has a broader impact. When Alexander Fleming discovered penicillin, his initial discovery did not have much impact. It was not until other scientists discovered how to produce penicillin and it was used to prevent infections in World War II that the impact and benefits of Fleming's work were realized.

1.3 Basic and Applied Science

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

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

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

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

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

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

1.4 Science Denial

Anti-evolution league at the infamous Tennessee v. Scopes trial.

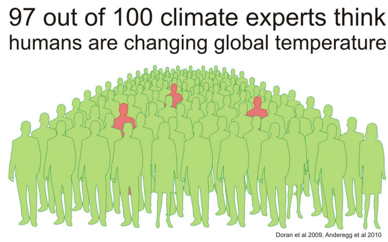
Introductory science courses usually deal with accepted scientific theoryAn accepted scientific idea that explains a process using the best available information.">theory and do not include opposing ideas, even though these alternate ideas may be credible. This makes it easier for students to understand the complex material. Advanced students will encounter more controversies as they continue to study their discipline. Continually re-evaluating theories based on new evidence is a hallmark of science. However, some groups of people argue that some established scientific theories are wrong, not based on their scientific merit but rather on the ideology of the group. This section focuses on how to identify evidence-based information and differentiate it from PseudoscienceA method of investigation the claims to be scientific, but does not hold up to full scientific scrutiny. Examples include astrology, paranormal studies, young-Earth creationism, and cryptozoology (i.e. the study of creatures like Bigfoot and the Loch Ness Monster).">pseudoscience.

2017 March for Science in Salt Lake City. This and other similar marches were in response to funding cuts and anti-science rhetoric.

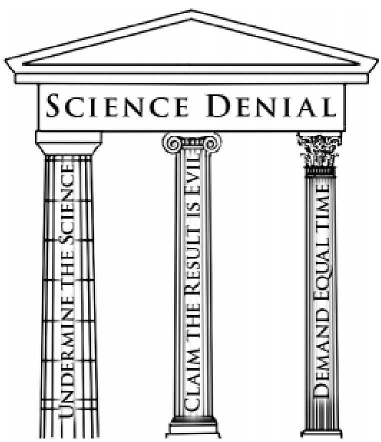
science denialThe act of purposely ignoring or dissenting from science for political or cultural gains.">**Science denial** happens when people argue that established scientific theories are wrong, not based on scientific merit but rather on subjectiveAn observation which is influenced by the observer's personal bias.">subjective ideology—such as for social, political, or economic reasons. Organizations and people use science denialThe act of purposely ignoring or dissenting from science for political or cultural gains.">science denial as a rhetorical argument against issues or ideas they oppose. Three examples of science denialThe act of purposely ignoring or dissenting from science for political or cultural gains.">science denial versus science are: 1) teaching evolution in public schools, 2) linking tobacco smoke to cancer, and 3) linking human activity to climateLong term averages and variations within the conditions of the atmosphere.">**climate** change. Among these, denial of climateLong term averages and variations within the conditions of the atmosphere.">climate change is strongly connected with geology. A climateLong term averages and variations within the conditions of the atmosphere.">climate denier specifically denies or doubts the objectiveAn observation that is completely free of bias, i.e. anyone and everyone would make the same observation.">objective conclusions of geologists and climateLong term averages and variations within the conditions of the atmosphere.">climate scientists.

science denialThe act of purposely ignoring or dissenting from science for political or cultural gains.">Science denial generally uses three false arguments. The first argument tries to undermine the credibility of the scientific conclusion by claiming the research methods are flawed or the theoryAn accepted scientific idea that explains a process using the best available information.">theory is not universally accepted—the science is unsettled.

The notion that scientific ideas are not absolute creates doubt for non-scientists; however, a lack of universal truths should not be confused with scientific uncertainty. Because science is based on falsifiability, scientists avoid claiming universal truths and use language that conveys uncertainty. This allows scientific ideas to change and evolve as more evidence is uncovered. For example, climate deniers argue that scientists do not all agree that humans are the primary cause of climate change. While this is technically true, the overwhelming majority of climate scientists, those scientists with expertise in the field agree.



Multiple review studies demonstrate that greater than 90% of all climate scientists agree that humans are changing global climate. Image from Skeptical Science (https://skepticalscience.com/graphics.php?g=1)



Three false rhetorical arguments of science denial (Source: National Center for Science Education)

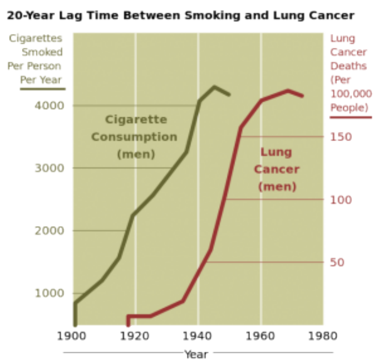
The second argument claims the researchers are not objectiveAn observation that is completely free of bias, i.e. anyone and everyone would make the same observation.">objective and motivated by an ideology or economic agenda. This is an *ad hominem* argument in which a person's character is attacked instead of the merit of their argument. They claim results have been manipulated so researchers can justify asking for more funding. They claim that because the researchers are funded by a federal grant, they are using their results to lobby for expanded government regulation.

The third argument is to demand a balanced view, equal time in media coverage and educational curricula, to engender the false illusion of two equally valid arguments. Science deniers frequently demand equal coverage of their proposals, even when there is little scientific evidence supporting their ideology. For example, science deniers might demand religious explanations be taught as an alternative to the well-established theoryAn accepted scientific idea that explains a process using the best available information.">theory of evolution [5; 6]. Or that all possible causes of climateLong term averages and variations within the conditions of the atmosphere.">climate change be discussed as equally probable, regardless of the body of evidence. Conclusions derived using the scientific methodThe idea in science that phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">scientific method should not be confused with those based on ideologies.

Furthermore, conclusions about nature derived from ideologies have no place in science research and education. For example, it would be inappropriate to teach the flat earth model in a modern geology course because this idea has been disproved by the scientific methodThe idea in science that phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">scientific method. Unfortunately, widespread scientific illiteracy allows these arguments to be used to suppress scientific knowledge and spread misinformation.

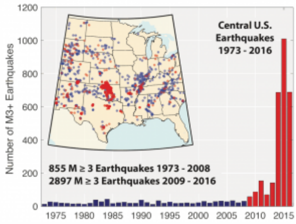
The formationAn extensive, distinct, and mapped set of geologic layers.">formation of new conclusions based on the scientific methodThe idea in science that phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">scientific method is the only way to change scientific conclusions. We wouldn't teach Flat Earth geology along with Plate tectonicsThe theory that the outer layer of the Earth (the lithosphere) is broken in several plates, and these plates move relative to one another, causing the major topographic features of Earth (e.g. mountains, oceans) and most earthquakes and volcanoes.">plate tectonics because Flat Earthers don't follow the scientific methodThe idea in science that phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">scientific method. The fact that scientists avoid universal truths and change their ideas as more evidence is uncovered shouldn't be seen as meaning that the science is unsettled. Because of widespread scientific illiteracy, these arguments are used by those who wish to suppress science and misinform the general public.

In a classic case of science denialThe act of purposely ignoring or dissenting from science for political or cultural gains.">science denial, beginning in the 1960s and for the next three decades, the tobacco industry and its scientists used rhetorical arguments to deny a connection between tobacco usage and cancer. Once it became clear scientific studies overwhelmingly found that using tobacco dramatically increased a person's likelihood of getting cancer, their next strategy was to create a sense of doubt about the science. The tobacco industry suggested the results were not yet fully understood and more study was needed. They used this doubt to lobby for delaying legislative action that would warn consumers of the potential health hazards [5; 7]. This same tactic is currently being employed by those who deny the significance of human involvement in climateLong term averages and variations within the conditions of the atmosphere.">climate change.



The lag time between cancer after smoking, plus the ethics of running human trials, delayed the government in taking action against tobacco.

1.5 Evaluating Sources of Information



This graph shows earthquake data. To call this data induced, due to fracking/drilling, would be an interpretation. Since the USGS (a reputable institution) has interpreted these earthquakes are

In the age of the internet, information is plentiful. Scientists, or anyone exploring scientific inquiry, must discern valid sources of information from PseudoscienceA method of investigation the claims to be scientific, but does not hold up to full scientific scrutiny. Examples include astrology, paranormal studies, young-Earth creationism, and cryptozoology (i.e. the study of creatures like Bigfoot and the Loch Ness Monster).">pseudoscience and misinformation. This evaluation is especially important in scientific research because scientific knowledge is respected for its reliability [8]. Textbooks such as this one can aid this complex and crucial task. At its roots, quality information comes from the scientific methodThe idea in science that phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">scientific method [9]. The application of the scientific methodThe idea in science that *caused by humans, it is a more reliable interpretation.*

phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">scientific method helps produce unbiased results. A valid inference or interpretation is based on objectiveAn observation that is completely free of bias, i.e. anyone and everyone would make the same observation.">objective evidence or data. Credible data and inferences are clearly labeled, separated, and differentiated. Anyone looking over the data can understand how the author's conclusion was derived or come to an alternative conclusion. Scientific procedures are clearly defined so the investigation can be replicated to confirm the original results or expanded further to produce new results. These measures make a scientific inquiry valid and its use as a source reputable. Of course, substandard work occasionally slips through and retractions are published from time to time. An infamous article linking the MMR vaccine to autism appeared in the highly reputable journal *Lancet* in 1998. Journalists discovered the author had multiple conflicts of interest and fabricated data, and the article was retracted in 2010.

The same rigor should be applied to evaluating the publisher, ensuring the results reported come from an unbiased process [11]. The publisher should be easy to discover. Good publishers will show the latest papers in the journal and make their contact information and identification clear. Reputable journals show their peer reviewA process where experts in a field review and comment on a newly-introduced work, typically a part of publication.">peer review style. Some journal are predatory, where they use unexplained and unnecessary fees to submit and access journals. Reputable journals have recognizable editorial boards. Often, a reliable journal will associate with a trade, association, or recognized open-source initiative. In addition to methodology, data, and results, the authors of a study should be investigated. When looking into any research, the author(s) should be investigated [10]. An author's credibility is based on multiple factors, such as having a degree in a relevant topic or being funded from an unbiased source.

One of the hallmarks of scientific research is peer reviewA process where experts in a field review and comment on a newly-introduced work, typically a part of publication.">peer review. Research should be transparent to peer reviewA process where experts in a field review and comment on a newly-introduced work, typically a part of publication.">peer review. This allows the scientific community to reproduce experimental results, correct and retract errors, and validate theories. This allows the reproduction of experimental results, corrections of errors, and proper justification of the research to experts.

Citation is not only imperative to avoid plagiarism, but also allows readers to investigate an author's line of thought and conclusions. When reading scientific works, it is important to confirm the citations are from reputable scientific research. Most often, scientific citations are used to reference paraphrasing rather than quotes. The number of times a work is cited is said to measure of the influence an investigation has within the scientific community, although this technique is inherently biased [12].

We are at a point in time when a large amount of information is available to inform us on various topics, including science. All we have to do is type a question into Google and a multitude of answers appear. At some points, it can be overwhelming and often difficult to determine if a source is credible. It is particularly important to understand the credibility of a source when using it as a means to support your arguments and when making life decisions. When evaluating any source, you should ask yourself the 3 Ws:

1. WHERE

Ask yourself where the source was published. Credible sources tend to be published in peer-reviewed scholarly journals or by a university press, professional society, or scientific publisher. This is because all of these sources of information are peer-reviewed, meaning they have been evaluated by experts in the field.

If the source is an online resource, you need to be particularly careful. It is not necessarily indicative of a poor resource, but it will depend on who published the information on the website. Generally, websites with a .gov or .edu will provide credible information. Conversely, a website like Wikipedia, though useful for quickly looking up information, is not a credible source to use because anyone can add and edit content, regardless of their expertise. Additionally, websites with a .com, .org, and other variations are often not credible sources based on biases associated with funding, a lack of people involved with the expertise to write the content, and a lack of peer-review. Also, keep in mind that there are some online journals (e.g. PlosOne) that will provide reputable, peer-reviewed journal articles.

2. WHO

Ask yourself who the author is. Do they work at a University or another reputable institution? What have they written and do they have expertise in the content they have written? Additionally, you may want to assess anyone that the author, particularly in news articles, has decided to quote or use as a resource. As an example, there is an article on the site Slate.com about invasive boa constrictors in the Everglades. Two of the people Slate chose to interview for the article are associated with the Skunk Ape Museum in Florida. What is a skunk ape? Well, it is a mythical creature. Consequently, the credibility of the article is questionable. You can read a blog post on the issues with the article here and you can see the original article at this link.

Also, you should consider who the intended audience of the article is. If the intended audience is a scholarly one, there should be a clear bibliography included with the source you can consult. This becomes particularly important when secondary sources are providing information from a journal article or some other peer-reviewed source. It is a good idea to go take a look at the original resource to be sure that the authors are correctly providing information and not overstepping the conclusions that can be drawn from the paper.

3. WHEN

Ask yourself when the article was written and if the content is outdated. Depending on the discipline, information can become outdated rapidly. You should look for additional texts on any given topic to be sure that the information provided is still relevant.

Test Yourself!

Go read this article (http://zapatopi.net/treeoctopus/) and use the 3 Ws to evaluate if it provides credible information.

For more information and practice, check out the Baloney Detection Kit

Summary

Science is a process, with no beginning and no end. Science is never finished because a full truth can never be known. However, science and the scientific methodThe idea in science that phenomena and ideas need to be scrutinized using hypothesizing, experimentation, and analysis. This can eventually result in a consensus or scientific theory.">scientific method are the best way to understand the universe we live in. Scientists draw conclusions based on objectiveAn observation that is completely free of bias, i.e. anyone and everyone would make the same observation.">objective evidence; they consolidate these conclusions into unifying models. Scientists generate knowledge and information through their work, but science is not just a collection of facts. In addition, scientific knowledge is always generated based on the systematic gathering of objective data, but it is not always generated by lab-based experiments.

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Huang, Ching-Yu; Crook-Hill, Janice; Collantes, Hugo; Darracq, Andrea K. (2018) Introduction to Ecology. University of North Georgia, Dahlonega, Georgia, USA.

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2. What do ecologists study?

When you go outside, take note of the organisms around you. At first, they will seem to be all alike; every tree seems like every other, with a trunk, branches, and leaves all fed by an underground root system. After a closer examination, differences soon become apparent, until it seems as though there are no similarities between individuals at all; each squirrel is a different size and behaving differently from all of the others and even each leaf seems slightly different. When taken as a whole, however, patterns will emerge in the behaviors, morphology, and geography of the organisms in the world; different kinds of trees are found on hilltops and others in valleys; the squirrels in one location might be bigger than those in another. Some birds tend to stick to the interior of the forest, while others are found mostly along the edges. Some of this variation seems obvious and unsurprising, and other aspects are subtle and require detailed measurements to uncover.

Examples of the different types of communities. A. high-elevation tropical forest, Costa Rica, B. Great Barrier Reef, Australia, C. tropical woodland, Northern Territories, Australia, D. Sonoran Desert, Arizona, USA, E. high-elevation meadow, Colorado, USA, F. temperate forest, Michigan, USA. (Photo credits: B. Richard Ling, Source: Wikipedia, all others S. Scheiner)

Living systems bear several major hallmarks, one of which is variation. While some variation is due to genetic differences among individuals, and some is due to differences in growth and development, there is a third cause of variation that must be taken into account. this is the external factors affecting individual organisms; in other words, the environment. Like many other aspects of biology, organisms and their environments form a complex set of interactions that feedback on each other.

2.1 The Theory of Ecology

The general theory of ecology consists of eight fundamental principles listed below. The roots of these principles can be traced to the origins of the science of ecology in the 19th century, the roots of which can be traced back through the study of natural history to ancient Greece. The word "ecology" comes from the Greek word "oîkos," meaning "house," indicating that ecology is the study of an organism's abode.

The eight fundamental principles of the general theory of ecology

1. Organisms are distributed unevenly in space and time.
2. Organisms interact with their abiotic and biotic environments.
3. The distributions of organisms and their interactions depend on contingencies (chance events).
4. Variation in the characteristics of organisms results in variation of ecological patterns and processes.
5. Environmental conditions, as perceived by organisms, are heterogeneous in space and time.
6. Resources, as perceived by organisms, are finite and heterogeneous in space and time.
7. Birth rates and death rates are a consequence of interactions with the abiotic and biotic environment.
8. The ecological properties of species are the result of evolution.

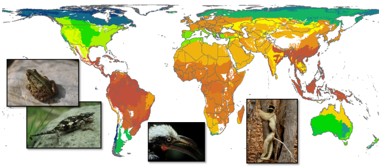
We will explore all of these fundamental principles throughout this textbook. Each principle is addressed briefly and individually below, but throughout the rest of the book, you will see that these principles are tightly intertwined. These principles are presented first to give you a sense of how the ecological information you will learn in this book relates.

Ecology emerged as its own discipline between 1880 and 1910, along with much of biology. The roots of many of today's ecological theories can be found in this period, although the fundamental principles emerged only slowly over the next 50 years. While all of the fundamental principles had been put forth by the middle of the 20th century, there were still serious debates about their relative importance. For example, the process of evolution in shaping global patterns of species distributions was recognized by Charles Darwin in the nineteenth century, but it was not until after the Modern Synthesis (see chapter 3) shaped the theory of evolution in the middle of the 20th century that there was extensive study of the interplay of ecological and evolutionary processes within local settings.

The domain of the science of ecology is the spatial and temporal patterns of the distribution and abundance of organisms, including causes and consequences. Strikingly, four of the eight fundamental principles are about variation of either the biotic or abiotic world. It is this focus on variation that makes ecological studies so challenging and exciting. In addition, ecology is the aspect of biology that pays the most attention to the world outside of the organism.

Because the science of ecology deals with interactions between organisms and the rest of the world, it is often linked with political concerns about the state of the world, which can be grouped under the heading of environmentalism. However, ecology is not environmental advocacy or political activism, although scientists are sometimes environmental activists in their personal lives, and environmental activists may, and should, rely on scientific research. Ecology itself is not about one's feelings about nature, although ecologists may have strong feelings about what they study.

2.2 Principle 1: Uneven distributions



Global patterns of terrestrial vertebrate diversity analyzed in the Chase J (2012) Historical and Contemporary Factors Govern Global Biodiversity Patterns. PLoS Biol 10(3): e1001294. doi:10.1371/ journal.pbio.1001294. Each of the 32 bioregions is colored by its vertebrate species richness (amphibian, reptile, bird, mammal richness combined; dark green represents the lowest values and dark red represents the highest values). This image by Johnathan Chase is available under the Creative Commons Attribution 2.5 Generic license.

Organisms are not uniformly distributed across the face of the Earth. As far back as 2500 years ago, Greek natural historians were aware that different species were limited in the types of habitats in which they were found. However, scientists first became aware of large-scale patterns in species diversity as a result of the voyages of exploration and colonization undertaken by Europeans in the 18th and 19th centuries. Their ships often carried botanists and zoologists as part of the crew, the most famous example being the voyage of the Beagle (1831–1836), on which Charles Darwin served as the ship's naturalist. These naturalists made records of the plants and animals they found, brought back specimens, and added them to the growing catalog of described species.

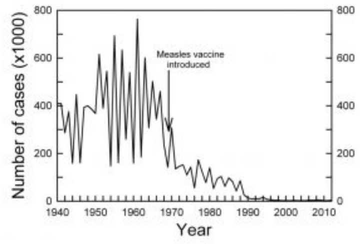
From these records, it soon became apparent that tropical regions were typically very rich in species, polar regions were very species-poor, and temperate regions had intermediate numbers of species. Brazil alone has over 56,000 named plant species, while the United States has about 18,000, and Canada has about 4200. An explanation for this pattern of more species in the tropics may be the oldest major ecological hypothesis. Between 1799 and 1804, Baron Alexander von Humboldt traveled through Mexico, Central America, and northwestern South America. He subsequently published a series of essays under the title *Ansichten der Natur* ("Views of Nature"), in which he described this pattern and postulated that it was due to differences in climate, specifically winter temperatures and the effects of freezing.

Prairie dogs are social animals live in family groups that are further clustered into towns. Those towns, however, are dotted across a landscape leading to a very uneven distribution of animals. (Credit: U.S. Fish and Wildlife Service/photo by Curtis J. Carley)

In contrast, creosote bushes are regularly distributed due to competition for water. (Credit: U.S. Geological Survey/photo by Sarah Studd)

Even within a single population of one species, individuals generally are not uniformly distributed. They may be concentrated in patches, as with prairie dogs in the western United States. Prairie dogs live in large colonies called towns; in northern Colorado, each town contains about 850 individuals and the towns are separated by an average distance of 50 km. Individuals of a species may also be evenly spread throughout the landscape, as is seen with populations of creosote bushes in the Sonoran Desert that are spaced out because of competition for water. Thisvariation in abundance extends even to the smallest species. Within your body are thousands of species of bacteria, with different species living in different places. Some reside exclusively in your stomach and intestine, while others cruise your blood vessels. Just within your mouth, each tooth harbors its own set of bacterial species and those species remain for months no matter how much you brush your teeth.

The number of individuals may also vary through time. For example, prior to the development of vaccines, many disease-causing viruses showed similar boom-and-bust cycles, with a sharp decline in the number of cases after vaccines were introduced. Not all change is cyclical, however. Following a major disturbance, such as a forest fire or a hurricane, the plants in a community will slowly change in composition. Immediately after the disturbance, some plants will resprout from still-living root systems and others will germinate from seeds that sat dormant in the soil or that are newly arrived at the site. The result can be a very different mix of species than were in that site prior to the disturbance. Over time the first species may be displaced by later arriving ones, until over the course of decades or centuries the original community reappears.



The monthly number of reported cases of measles in England and Wales (1940 to 2012). The number of cases dropped substantially after the initiation of a national vaccination program. (Source: Office of National Statistics and Department of Health, UK)

The trees on this site in northern Michigan were logged and the site burned.

The following summer, new aspen trees sprouted from the roots of the previous trees.

A century following cutting and burning, the forest is now dominated by a mixture of white pine, red maple, and red oak trees. (Photos: S. Scheiner)

Change also occurs over much longer time spans. For the past 2 million years the Earth has been in the midst of a glacial period. During that time glaciers have waxed and waned at least four times. In North America, at the height of the last advance, glaciers extended as far south as the region around the Great Lakes. At that time forests were found only in what is now the southern United States. For the past 20,000 years, we have been in a period of glacial retreat and those forests have migrated to northern Canada. Over even longer time spans, however, some patterns are extremely stable. For example, the pattern of many species in the tropics and few at the poles is very old, going back at least to the time of the dinosaurs 100 million years ago.

Thus, the number of individuals in a population or the number of species in a community are dynamic. This dynamic aspect of ecological systems contrasts with an older view of the world existing in a "balance of nature," an idea which goes back at least 2500 years to the Greek historian Herodotus, and was the prevailing view into the first half of the 20th century. While scientists recognized that communities changed following a disturbance, the notion was that communities tended to return to an equilibrium in which all plants and animals were at numbers sufficient to sustain the entire system. These ideas were most notably put forward in modern science by Fredric Clements, who formulated the first theory of change in plant communities. We now know that the idea that nature is in balance is wrong. Not only are systems dynamic, populations are often disappearing from a given site and replaced by other species or perhaps reappearing as new individuals move back into the system.

2.3 Principle 2: Biotic and abiotic interactions

All organisms live within a larger environment and, by necessity, interact with that environment; these interactions in turn determine the distribution and abundance of organisms. For simplicity, we can divide those interactions into ones involving the **abiotic** (non-living) parts of the environment, and those involving the **biotic** (living) parts. The nature of those interactions vary depending on whether the organism is a plant or an animal, single-celled or multicellular, and more, but the basic nature of those interactions is the same for all species.

One common aspect is how the environment affects an individual's body temperature. For example, when you jump into water that is cooler than you are, you feel chilly. You do not get cold as quickly as a smaller animal would, however, because your greater mass stores more heat energy. If you were to begin swimming vigorously, the metabolic energy produced by your muscles from burning stored calories would warm you up. Because you are a mammal, you maintain a constant body temperature using that metabolic energy. Most organisms, however, do not. Their body temperature depends on absorbing energy from the environment, energy which we label "heat" or "light." This is just one example of organisms' interactions with the abiotic environment.

Mushrooms are the reproductive structures of fungi. Many fungi obtain their food by breaking down dead tissues. (Photo: S. Scheiner)

An example of a biotic interaction is when an organism consumes others for food usually by either consuming it while still alive, killing the other organism, or eating an organism that another animal has just killed or has recently died. This can include a group of lions chowing down on a zebra , or the vultures that feast on the carcass once the lions are done. Such consumption is called **predation**. Some organisms take in organic molecules from other organisms that are already dead, or from dead tissues such as the skin that you are constantly shedding. These latter organisms include most fungi and many bacteria.

When one organism eats another, the eater gets a benefit while the eaten suffers a cost. Many times that cost is death, but not always. When you harbor a cold virus, it will reproduce inside you and get passed on to others while only causing you a few days of illness. Most of the time when a plant gets eaten, only part of the plant gets taken, such as a caterpillar munching on a leaf. Thus, the amount of benefit and cost to each of the participants in the interaction can vary. Nor are interactions always of the type where one participant benefits while the other suffers a cost. Many types of interactions benefit both participants and are termed **mutualisms**. An obvious example is when a hummingbird visits a flower. The hummingbird drinks the nectar from the flower, a solution very high in sugar. At the same time, the hummingbird gets pollen deposited on its head. When the hummingbird visits the next flower, the pollen from the first gets left behind. Importantly, that next flower will generally be one of the same species, so that the pollen can fertilize that flower. Thus, the hummingbird gains energy and the flower gets its pollen moved to exactly the right place.

All of the interactions just described are direct, one individual doing something to another. But interactions can also be indirect. For example, there is a finite number of zebras, and if one gets eaten by a lion, that leaves fewer zebras for other lions or hyenas to eat. Indirect effects can also occur through changes in the abiotic environment. An especially dramatic example involves the actions of beavers. Beavers cut down trees and use the wood to build dams across streams, which causes the surrounding area to flood. Just like a manmade dam and attendant reservoir, this creates ponds within which the beavers build houses – creating a place protected from predators. In doing so, they change the environment. By flooding an area, they increase the amount of water in the soil around the pond as well as the amount of light on the area by removing the trees. Some plant species grow much better in areas with lots of light and very wet soil, so they indirectly benefit from the beavers' activities, while other species are excluded by those changes. While ecologists have always worked to understand these interactions, such efforts were greatly enhanced with the movement towards descriptions through mathematical models. These interactions and their impacts on all levels of organization will be covered in more detail in later chapters.

2.4 Principle 3: Contingency

Chance can play both a small and large role in the abundance and distribution of organisms. Consider a field with many different species of plants, including grasses and wildflowers, such as goldenrod. Each year the goldenrod individuals produce seeds that get blown about in the wind, landing in various places in the field. Some of those places are not near any other plants, and thus are good places to germinate and grow; other seeds will end up next to or directly underneath another plant, so the plants that germinate from those seeds may not grow very big or may simply die. Chance dictates how many seeds land in good places and which seeds those are. Once the seed starts to grow it must compete with the other plants around it for light and for the water and nutrients in the soil. Goldenrod is very different in form from the grasses in that field, and so does not compete very much with them. However, say that asters also grow in that field. Those plants are similar to goldenrods and so compete a bit more. And, of course, two goldenrods growing next to each will compete quite a bit. In addition to simple placement, which species an individual happens to be growing next to also depends a great deal on chance.

Goldenrod (Photo: A. Pethan, Wikimedia Commons)

Aster (Photo: Kurt Stueber, Source: Wikimedia Commons)

At much larger scales, the same sort of process can be seen. On the continent of Australia, the dominant mammals are marsupials like kangaroos and koalas. Placental mammals like humans and horses had not spread to Australia before that continent was separated from Africa, South America, and Antarctica. That chance event led to many differences in the animals of Australia and a wide-range of animals, such as koalas, kangaroos, wallabies, and Tasmanian devils, found only in Australia. Up until 40,000 years ago, the largest plant-eater was the *Diprotodon*. It grew to about 3 m in length and 2 m in height and weighed about 2500 kg. It mostly ate leaves of trees and shrubs and some grass. In many ways, it was similar to an elephant, but not as large.

Ecologists have debated for many decades about the importance of chance. For the most part, in the first half of the 20th century, most ecologists thought that chance played a relatively small role, although there were always some dissenters. The most vigorous debates were about the role of chance in changes in population numbers, a debate that was renewed about once a decade. This debate intensified during the 1960s and spread to other aspects of individual and species numbers and distributions; as it spread, this debate spurred the rapid development of mathematical models through which the effects of chance could be tested. Finally, by the 1980s most ecologists agreed that chance events could play a significant role in most ecological processes. It is no coincidence that this increase in the appreciation for the importance of chance happened at the same time that computers were becoming faster and easier to use. Models that incorporate random variation require fast computers for implementation. This linkage of computer technology and a change in ecological theory is an example of how changes in technology can drive scientific advancement.

2.5 Principle 4: Variation Among Individuals

No two individuals are ever identical. Even individuals that are genetically identical grow up under slightly different circumstances resulting in differences in form or behavior. Differences become more and more apparent the more genetic variation is involved: collections of individuals, populations, will also differ from each other, and most noticeable are the differences between species, many of which are caused by natural selection (see Chapter 3). All of these types of variation can affect ecological patterns and processes and understanding those effects can have important practical implications when it comes to species conservation.

Because population numbers naturally cycle up and down, one cause of local extinction of that population is if the changes in the environment lead to the death of just a few more individuals during one of those down phases, causing the population numbers to drop to zero. For example, an especially cold winter may result in a few more individuals freezing to death, or a bad drought may mean more plants die from insufficient water. If all of the individuals in a population were identical, then the chance of every individual dying in especially adverse conditions would increase. However, if during that drought, some of the plants are more resistant to drying out or better able to tolerate drying out, then their chance of survival will be greater and at least some individuals will survive. Then, when conditions improve the population numbers will again rise.

Variation among species can have similar effects on the stability of entire communities. For example, plant species differ in their ability to grow given different amounts of water. Some species grow best under drier conditions, while others grow best under wetter conditions. Since rainfall can vary substantially from one year to the next, a plant community that contains a diverse array of species varies less in total growth from year to year than a community consisting of just one or two species. In the diverse community, at least a few species can grow well under any given amount of rainfall, thus maintaining a minimum biomass. Species diversity alone, however, is not the only factor that affects the structure of communities. As food webs increase in number of species, they can become more sensitive to small disturbances because a change in the number of individuals in one species quickly affects all of the other species. However, if the food web consists of some species that are tightly linked to each other (e.g., a predator that specializes on a single prey species) and others that are only loosely linked (e.g., a predator that eats lots of different species so that it does not rely on any single prey species), then changes in species numbers in one part of the food web do not affect those in other parts.

2.6 Principle 5: Environmental conditions

Variation in a species' location is caused by many factors, one of which is variation in the environment. As shown above, the greatest numbers of species are found in equatorial regions and the fewest numbers are found in polar regions and deserts. This variation in species numbers is associated with differences in annual temperatures and rainfall. In general, more species are found in warmer and wetter environments. This pattern of differences in temperature and rainfall corresponding to differences in species are also found across continents and even at distances of tens of kilometers. In addition to distance, time also creates variations; the environment varies in the same site from day to night, from week to week, and across seasons. The Earth itself has been subject to much longer cycles, such as the advance and retreat of glaciers over tens of thousands of years.

A rocky coast at low tide along the Pacific Ocean in Washington Different organisms can live at different heights depending on their tolerance for drying, with the most tolerant living at the highest distance from low tide. (Credit: Bcasterline, Source: Wikipedia)

All aspects of the environment vary, each having its own effects on the distribution of organisms. At the ocean's shore, for example, are places that are always underwater, others that are dry part of the day and wet at other times as the tides go up and down, and others that only occasionally get wet, leading to very different species in those various zones. Few plants can grow in soils with high amounts of salt, so the spray from the waves limits which species grow near the shore.

Environmental variation occurs at very short distances and across the entire globe, from moment to moment and from aeon to aeon. As dramatic as this variation can be, not every aspect of it affects all species equally. The relative importance depends on the organism; what a bacterium perceives is not what an elephant perceives. For a bacterium, differences in soil nutrients over distances of micrometers can be critical, a distance that would make no difference to an elephant. A squirrel may live and die within a year, while the oak tree that it climbs might live for hundreds of years. Changes in climate that take decades to happen are not experienced by the squirrel, but can be vital to the life of the oak tree.

These large differences in the scale and pace of environmental variation pose challenges to scientists trying to understand the interaction between organisms and their environment. For small organisms, experiments can be done in a laboratory or greenhouse. For global-scale processes, manipulative experiments are not possible, so scientists must rely on mathematical models using correlations between environmental factors and species distributions to formulate these larger-scale theories. Such observational experiments have limitations in what they can tell us about causal mechanisms and are best when they can be paired with manipulative experiments. In the past few decades, scientists have been performing much larger and longer manipulative experiments that have provided new insights into ecological processes.

2.7 Principle 6: Finite resources

An important distinction among types of environmental factors are conditions versus resources. Conditions are unaffected by organisms – for example, temperature is a condition in that it affects the organism, but no matter how warm or cold the organism gets the organism does not increase or decrease the amount of heat in the broader surrounding environment. In contrast resources are finite and potentially depleted by organisms. If foxes are eating rabbits, there are only so many rabbits to go around. Every rabbit eaten means one fewer available for another animal to eat. Resources, therefore, are subject to competition, unlike environmental conditions; both environmental conditions and resources, however, vary in space and time. The heterogeneity of resources has a number of causes. Variation in environmental conditions can have indirect effects on the distribution and abundance of species through their affects on organisms that serve as resources. The processes that cause variation in resources are often the same as those that cause variation in environmental conditions. For example, seasonal variation in light and temperature are caused by the movement of the Earth around the Sun. However, light is subject to competition (e.g., when one plant shades another) whereas temperature is a condition and not subject to competition.

Whether a particular environmental factor is a condition or a resource is context dependent. For example, water is sometimes a resource subject to competition (e.g., plants in a desert) and sometimes a condition (e.g., fish in the ocean). Some elements (e.g., manganese) can be limiting to plants at low levels, thereby acting as a resource. On the other hand, that same element can be toxic at high levels, in that case acting as a condition. Thus, while the distinction between conditions and resources is important, the two categories blur into each other. Both resources and conditions control where a species can live, but only resources are capable of being depleted.

2.8 Principle 7: Birth and death

The evolutionary fitness of an organism is the result of that individual's life history and reproduction (see Chapter 3). An organism's birth and death processes and rates are at least partially dependent on the environment of the organism, both conditions and resources.

For example, reproduction requires resources to build new cells beyond those needed for survival. The rate at which an organism reproduces – for example, how quickly a single-celled organism can divide or how many eggs a bird can lay – depends on the rate at which that individual can take up nutrients from the environment. It is more than simply how fast an animal can eat, however. Often, one particular nutrient, such as phosphorus, will be the limiting factor. Sometimes the limiting resource is other individuals of the same species. The limitation may be due to competition or, in some circumstances where individuals are widely separated, such as tigers where each adult male or female will control a large territory, simply finding another individual to mate with can create limitations on the rate of reproduction. Death rates similarly also depend on availability of resources, environmental conditions and the presence of other species.

Competition for limited resources determines the number of individuals that can live in an area. Such competition can occur between individuals within a species – Canada lynx competing for snowshoe hares – or among different species – arctic foxes eating those same hares. If the persistence of a population depends on it being above some minimum size, the amount of available food would limit not just the number of individuals but also the number of species. Consider, for example, if the minimum population size of both the lynx and fox was 100 individuals; there would have to be enough hares for 200 individuals for both species to be able to persist in an area. If there were only enough hares for 120 individuals, then one species would go locally extinct.

2.9 Principle 8: Evolution

The process of change over generations (evolution) and environmental interactions (ecology) are intertwined. The biology of organisms creates the context within which evolution occurs and, in turn, evolution determines the properties of organisms. The environment creates context in two ways. First, the characteristics of an organism are determined both by the environment within which the organism's genes are expressed and the organism's genes. In other words, the appearance and other characteristics of an organism are determined both by the organism's genetics and its environment. Second, the relationship between the characteristics of an organism and its fitness is determined by the organism's abiotic and biotic environment; thus, the direction of natural selection is a function of the environment (see Chapter 3).

It may seem obvious that the ecology of an organism has been shaped, at least in part, by its evolutionary history. But such evolutionary thinking was not always common among ecological scientists. The inclusion of evolution within ecological thinking was an important outcome of the Modern Synthesis (see Chapter 3). Although evolutionary thinking about ecological processes goes back at least to Darwin, evolutionary thinking began infusing ecology in a significant way in the 1920s and its widespread acceptance occurred primarily in the latter half of the 20th century.

Even today, most ecological studies do not take into account evolutionary processes. In some instances, evolution can be safely ignored, particularly when the time period consider includes only a few generations of the studied species. On the other hand, when studying very long time periods or species with short generation times (the time between successive generations), evolutionary processes may be important. For example, cycles of measles outbreaks may be affected by evolution, as even within a single person the measles virus is going through many generations allowing many opportunities for mutation and new genetic variation.

Such interactions of ecology and evolution can be seen when two species interact and evolve in response to each other. Consider the case of the Australian wild flax plant and a fungus that can infect it, causing flax rust. A long-term study was undertaken in southeastern Australia beginning in 1986. In 1990, the population being monitored suddenly crashed, dropping from a density of 22.6 individuals/m^2 to 8.5 individuals/m^2 in just one year. A new strain of rust had appeared in the population, one to which most plants were susceptible. However, within a single year the percentage of the population that was resistant to that new strain increased from about 3% to over 20%, and as a result the numbers of individuals in the population began to climb[1]. This change in the average

1. Burdon, J., & Thompson, J. (1995). Changed Patterns of Resistance in a Population of Linum Marginale Attacked

resistance of the population is an example of very fast evolution in response to strong natural selection.

These principles will be explored in more depth through the textbook, beginning with an exploration of evolution.

Levels of Ecological Study

Within the discipline of ecology, researchers work at four general levels, which sometimes overlap. These levels are organism, population, community, and ecosystem

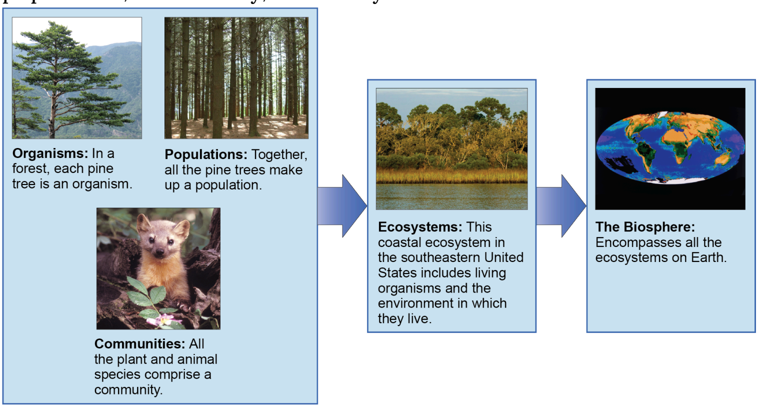


Figure. Ecologists study within several biological levels of organization. (credit "organisms": modification of work by yeowatzup"/Flickr; credit "populations": modification of work by "Crystl"/Flickr; credit "communities": modification of work by US Fish and Wildlife Service; credit "ecosystems": modification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

by the Rust Pathogen Melampsora Lini. Journal of Ecology, 83(2), 199-206. doi:10.2307/2261558

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 44.3) is considered a specialist because the females only *oviposit* (that is, lay eggs) on wild lupine (*Lupinus perennis*). This specific requirement and adaptation means that the Karner blue butterfly is completely dependent on the presence of wild lupine plants for its survival.

Figure 44.3 The Karner blue butterfly (*Lycaeides melissa samuelis*) is a rare butterfly that lives only in open areas with few trees or shrubs, such as pine barrens and oak savannas. It can only lay its eggs on lupine plants. (credit: modification of work by J & K Hollingsworth, USFWS)

After hatching, the (first instar) caterpillars emerge and spend four to six weeks feeding solely on wild lupine (Figure 44.4). The caterpillars pupate as a chrysalis to undergo the final stage of metamorphosis and emerge as butterflies after about four weeks. The adult butterflies feed on the nectar of flowers of wild lupine and other plant species, such as milkweeds. Generally there are two broods of the Karner blue each year.

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

Figure 44.4 The wild lupine (*Lupinus perennis*) is the only known host plant for the Karner blue butterfly.

Population Ecology

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

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

Community Ecology

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

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

Ecosystem Ecology

Ecosystem ecology is an extension of organismal, population, and community ecology. The ecosystem is composed of all the biotic components (living things) in an area along with the abiotic components (nonliving 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 through 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.

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- **Samuel M. Scheiner and Kayla I. Scheiner**

Levels of Ecological Study – adapted from OpenStaxs Biology 2e by Mary Ann Clark, Matthew Douglas, Jung Choi.

- Access for free at https://openstax.org/books/biology-2e/pages/1-introduction

PART II
GLOBAL CLIMATE CHANGE

Before really delving into a discussion of climate change, we have to begin with some clarification of terms: **weather** vs **climate** and **global warming** vs **climate change**. All of these terms relate to atmospheric conditions, specifically temperature, but understanding the differences is crucial to understanding climate change.

Many of us check the weather every day. This automatically indicates that weather is something that changes frequently. When we watch a storm move in across the ocean, feel the humidity after a rainstorm or feel the temperature cool in the evening, we are observing a change in the weather. Weather is the atmospheric conditions, temperature, humidity, precipitation, wind speed and more, at a specific location at a specific time. Climate is the long-term average of these conditions, often at the regional or larger scale. Single days, weeks, or even years that are hotter than normal or rainier than normal, do not indicate a change in climate. However, a long-term trend of changes in temperature and/or precipitation do indicate a change in climate.

Global warming is a change in climate but is not synonymous with climate change. Global warming just refers to the trend of increasing global temperatures (we will talk about evidence of this in a minute). Global warming is a part of climate change, but climate change includes changes in precipitation and extreme events such as droughts and heat waves. Both terms are appropriate as long as they are used correctly. For a more thorough discussion of global warming vs. climate change, read this article from Skeptical Science.

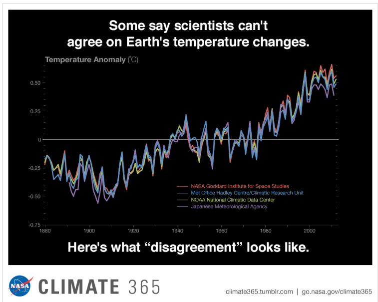
How do we know that climate is changing?

Climate has always been changing, but the changes we are currently seeing are unprecedented. Measuring the weather at a given location is fairly easy, but studying long-term changes in climate is more difficult, especially because we only have direct measurements with modern, or reasonably modern, instruments for about the last 100-150 years, with most weather stations in the United States established in the 1800's. Because of this, climate researchers must use direct and indirect measurements to look at long-term patterns in climate.

When scientists need to examine climate from time periods before direct, recorded measurements of climate, they use **climate proxies**. For example, oxygen is found in both "light" and "heavy" forms on Earth, with the heavy forms having additional protons. The "heavy" form tends to form clouds and rain more easily than the "light" form does. Similarly, the "light" form evaporates more easily. Because of this, the two forms of oxygen accumulate differently in ocean water and in land ice depending on the temperature. Scientists can then use oxygen trapped in ocean sediments and ice cores to determine past climate. Scientists can also use evidence from coral reefs, which have rings indicating years of growth. Because coral grow faster in warm water, the width of these rings can be used to reconstruct past climate. These reconstructions of past climate are not simple, but the overwhelming evidence, from both modern measurements and reconstruction of past climate, is that climate is rapidly changing.

Our evidence of climate change includes warming global temperatures, increasing ocean temperatures, shrinking glaciers and sea ice, declining snow cover, sea level rise, and increasing frequency of extreme events

Warming global temperatures



The temperature records from the four major scientific institutions recording global temperature each year show similar trends in warmer and colder years and all showing a trend of increasing temperature.

One of the most obvious sources of evidence of changing global climate is our record of global temperatures. Four major scientific organizations compile measures of the global average temperature each year and calculate a temperature anolmaly, the difference in the measured temperature from average temperature from 1950-1981. The temperature anomaly is calculated by subtracting the average temperature from 1951-1980 from the average temperature in a given year. Numbers greater than zero indicate that the temperature was hotter than it was from 1951-1980 while temperatures below zero indicate that it was colder than it was from 1951-1980. While these agencies do not all calculate the exact same number each year, data from all of the agencies show similar peaks and valleys and all show a compelling trend of warming temperatures (Fig. 1). When we examine the temperature record from 1880 to present, nineteen of the 20 warmest years all have occurred since 2001, with the exception of 1998. The years 2016 and 2020 are effectively tied as the warmest on record (Source: NASA/GISS). Scientist from both NASA (National Aeronautics and Space Administration) and NOAA (National Oceanic and Atmospheric Administration) use similar data to calculate the global average temperature and NOAA ranks 2020 as slightly cooler that 2016, while NASA finds the average temperatures to be the same (Source: https://www.nasa.gov/press-release/2020-tied-for-warmest-year-on-record-nasa-analysis-shows). These slight differences do not undermine the key message of the yearly analyses by NASA and NOAA, that the planet is getting hotter overall. The planet's average surface temperature has risen by about

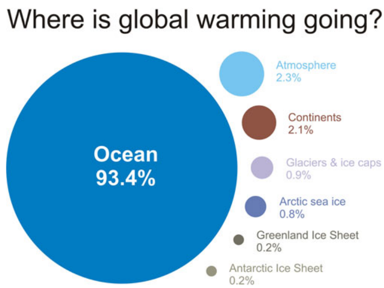
2° F (over 1°C) since 1880 and this temperature increase cannot be explained by variability in the data (https://www.giss.nasa.gov/research/news/20190523/). Most of the warming occurred in the past 35 years, with the six warmest years on record taking place since 2014.

Within this trend of warming, we see periods in which the climate appears to be cooling. For example, the global average temperature in 2018 was lower than the global average temperature in 2017, which was lower than the global average temperature in 2016. However, when this small piece of data is viewed in the context of long-term climate data, the warming trend is clear as seen in the video below (Credit: NASA/JPL-Caltech).

A video element has been excluded from this version of the text. You can watch it online here: https://viva.pressbooks.pub/theecosphereandenvironmentalissues/?p=30

Increasing ocean temperatures

The changes in temperature are not evenly distributed across the globe and one and one area of particular concern is the warming oceans. Not only do the oceans cover about 70% of the Earth's surface, the oceans are also highly effective at absorbing heat with relatively small changes in temperature. This ability to absorb heat is related to the heat capacity of water and, along with the latent heat, is a significant part of the oceans' role in stabilizing the Earth's climate. Heat capacity is the amount of energy required to increase the temperature of a substance by 1°C and is standardized by the mass of the substance to give specific heat. For example, if the specific heat is 1000 J/(kg °C), this means that it takes 1,000 J (a unit of energy) to increase the temperature of 1 kg of the material by 1°C. The specific heat of water is much greater than the specific heat of other materials commonly found on the Earth's surface (Table 1). Over 90% of the heat absorbed by the Earth in the last 50 years has been absorbed by the oceans, with most of the heat absorbed in the upper ocean (0-700 m deep). The upper ocean has warmed by about 0.2°C since 1969. This temperature increase is much smaller than the increase in temperature we have seen for the Earth as a whole, but represents a large amount of heat energy. A rough estimate of the amount of heat energy absorbed by the upper ocean during this time is 2×10^{23} J, or 2,000 times the total energy use of the United States in 2019 (see Box 1). While the temperature change in the ocean is smaller than the temperature change on land, the amount of energy required to produce this temperature change is clear evidence of a changing climate.



A visual depiction of how much global warming heat is going into the various components of the climate system for the period 1993 to 2003, calculated from IPCC AR4 5.2.2.3. Note that focusing on surface air temperatures misses more than 90% of the overall warming of the planet. This image is from Skeptical Science (the original can be found at https://www.skepticalscience.com/graphics.php?g=12)

Table 1. Specific heat of select materials commonly found on the Earth's surface. All data are from The Engineering Toolbox (https://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html and https://www.engineeringtoolbox.com/sea-water-properties-d_840.html)

Material	Specific heat (J/(kg °C))
Air (dry, sea level)	1005
Asphalt	920
Granite	790
Ice (snow, -5°C)	2090
Sand, quartz	830
Soil,dry	800
Soil, wet	1480
Seawater (20°C)	4007

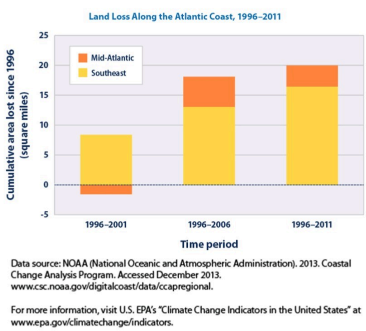
Sea level rise

The increasing ocean temperatures are closely related to sea level rise. While we know that water continuously cycles around the world, and that the overall quantity of water on Earth will not change due to global climate change, the distribution of this water is changing. In particular, oceans are increasing in volume while land ice stores (such as **glaciers**) are decreasing. This contributes to an increase in sea level worldwide.

Sea level has increased at an average of 0.06 inches (0.15 cm) per year from 1880-2014. Most of this rise, however, has occurred within the most recent decades. The rate of increase has gone up to between 0.11 to 0.14 inches (0.28 to 0.36 cm) per year since 1993. There are two forces causing sea level to rise, both caused by climate change. First, the increased global temperature has caused increased ice melting in many regions of the globe. Melting **land ice** contributes to sea level rise because water that used to be stored in ice sitting on top of land becomes running water which reaches the ocean through **runoff**. We also observe **sea ice** melting (see http://www.epa.gov/climatechange/ science/indicators/ index.html for data and figures). Sea ice, such as the ice that covers the arctic regions of the Northern Hemisphere, has no land underneath it. When it melts, the overall sea level does not change because the sea ice was already displacing ocean water of the same volume as the water it becomes when it melts. You can read and here more about land ice and sea ice at https://yaleclimateconnections.org/2014/11/loss-of-land-ice-not-sea-ice-more-sea-level-rise/.

The second factor that influences sea level rise is a phenomenon called **thermal expansion**. Due to the physical properties of water, as water warms, its density decreases. A less dense substance will have fewer molecules in a given area than a more dense substance. This means that as the overall temperature of the oceans increases due to global climate change, the same amount of water molecules will now occupy a slightly larger volume. This may not seem significant, but considering the 1.3 billion trillion liters (264 billion gallons) of water in the ocean, even a small change in density can have large effects on sea level as a whole.

Scientists have already documented sea level rise in some areas of the world, including one familiar to most of us: the Southeastern United States. The figure below depicts the measured land area lost due to increasing sea level since 1996. This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011. The results are divided into two regions: the Southeast and the Mid-Atlantic. Negative numbers show where land loss is outpaced by the accumulation of new land. Note that the Southeast (defined here as the Atlantic coast of North Carolina south to Florida) is particularly susceptible to land area loss due to the gently sloping nature of our coastline. Moving northward into the Mid-Atlantic States (defined here as Virginia north to Long Island, New York), coastal habitats tend to have a steeper geography, which protects against some losses.



While the ecological effects of sea level rise remain in the United States, we don't project any catastrophic loss of life, property, or livelihood for some time. This is, in part, due to large investments that we have made in infrastructure to protect our cities and farmlands. This is not the case in many areas of the world. For a discussion of the impacts of sea level rise on less-industrialized nations of Bangladesh, Maldives, Kiribati, and Fiji, review the required article reading.

Ocean acidification

Dissolved CO_2 is essential for many organisms, including shell-building animals and other organisms that form a hard coating on their exterior (e.g., shellfish, corals, Haptophyte algae). This hard coating is built out of **aragonite**, a mineral form of the molecule **calcium carbonate**, $CaCO_3$. These organisms rely on the formation of **carbonate** ions , CO_3^{2-}, from dissolved CO_2, through a natural, chemical reaction that occurs. This takes place through a chain-reaction equation, where **bicarbonate** (HCO_3^-) is formed as an intermediate, and **hydrogen ions** (H^+) are generated (**equations 6.3** and **6.4**).

$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^-$ **Eq. 6.3**

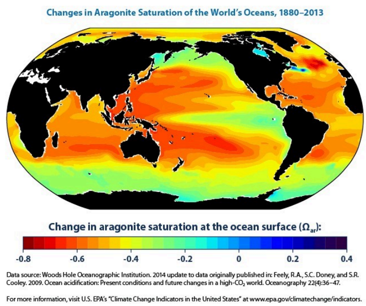
$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$ **Eq. 6.4**

To have a better visualization of this process, follow along with the interactive graphic at:

http://www.whoi.edu/home/oceanus _images/ries/calcification.html.

As you can see, both equations 6.3 and 6.4 each produce one H^+. This is significant to water chemistry because an increase in H^+ concentration means a decrease in the **pH** of the water. You can see in Figure 6.18 that a lower pH means that the liquid is more **acidic**. As shown in the interactive graphic, an increase in CO_2 in the atmosphere causes additional CO_2 to be dissolved in the ocean. This means that more CO_2 in the atmosphere leads to more acidic ocean environments.

Unfortunately for shell-building animals, the buildup of H^+ in the more acidic ocean environment blocks the absorption of calcium and CO_3^{2-}, and makes the formation of aragonite more difficult. An aragonite deficit is already being documented in many of the world's oceans, as shown below. This map shows changes in the aragonite saturation level of ocean surface waters between the 1880s and the most recent decade (2004–2013). Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. A negative change represents a decrease in saturation.

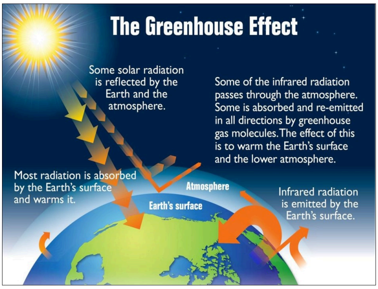


The increasing acidity of the world's oceans is resulting in habitat changes across the globe. This is only expected to worsen as atmospheric CO2 levels continue to increase. Many organisms, including the corals that are the foundation species of the beautiful coral reefs, are very sensitive to changes in ocean pH. Scientists have documented cases of ecosystem destruction through **coral bleaching**, caused by the effects of climate change including ocean acidification and increased temperature. For more information, visit the NOAA Coral Reef Conservation Program website: http://coralreef.noaa.gov/threats/climate/.

What is causing global climate change?

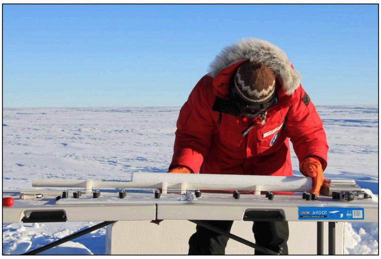
Scientists have identified the source of our current global climate change as being the increased human-caused emissions of greenhouse gases such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), since the industrial revolution. Greenhouse gases are defined as large (at least three atoms) gas molecules that participate in the **greenhouse effect**. While you already know about the "big three" greenhouse gases (CO2, CH4, and N2O), it's important to realize that **water vapor** (H2O) is also a greenhouse gas. While humans have little direct impact on water vapor concentrations in the atmosphere, is it still an essential component of the natural greenhouse effect that occurs in our atmosphere.

The Earth receives energy from the sun and in turn radiates energy back into space. When these two energies are equal, a stable temperature of the Earth is achieved. This temperature can be calculated from basic physics and is equal to about -18°C (0°F). This **thermal equilibrium temperature** is obviously much colder than that of the surface of the Earth. The actual average value of the Earth's surface temperature is about 15°C (59°F). The difference between these temperatures is due primarily to the natural greenhouse gas concentrations in the atmosphere, causing the greenhouse effect. If the Earth had no naturally occurring atmospheric greenhouse gases, the temperature at the surface of the Earth would equal the thermal equilibrium temperature. The influence of these greenhouse gases, mainly water and some CO2, moderates the Earth's climate and makes life possible.

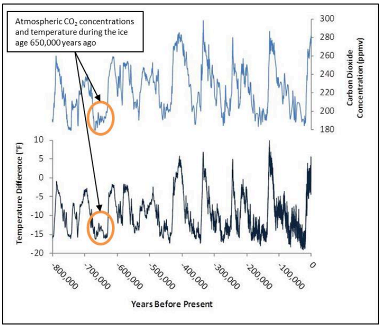


As **solar radiation** reaches the Earth's atmosphere, there are a variety of possibilities for its fate. Some solar radiation is reflected by the Earth and its atmosphere, and does not contribute to warming. Some passes through the atmosphere and reaches the surface of the Earth. When this solar radiation is absorbed by objects on Earth's surface, it is re-emitted as infrared radiation (heat) that escapes to space. However, some of this heat is intercepted in the atmosphere by greenhouse gases. These gases absorb and re-emit the radiation in all directions. This creates a warming impact on the Earth's surface Radiation can be bounced around from one greenhouse gas molecule to another, becoming trapped, and increasing its warming potential. For this reason, an increased greenhouse gas concentration causes an increase in the overall warming potential of the Earth's atmosphere.

On a geological time scale, the climate has changed many times in the past, even before the presence of humans. These changes occurred naturally because man had not yet evolved. A well-known example of past climate change is the occurrence of **ice ages**. Ice ages have occurred repeatedly throughout Earth's history, the most severe ice age of which scientists have reliable data occurred around 650,000 years ago. During this time, solid, glacial ice covered much of Canada, the northern United States, and northern Europe; the level of the ocean decreased 120 m, and the global average temperature decreased by 5°C. A geologic history of ice events is preserved in the ice sheets covering Antarctica and



Greenland. This history has been uncovered over the past decades by scientists who have cored deeply into the ice and deciphered the temperature and atmospheric composition records stored in the ice. This process of obtaining **ice cores** is shown on the left. On Dec. 8, 2010, Michelle Koutnik, of the University of Copenhagen's Center for Ice and Climate, prepared a core of Antarctic ice to be wrapped and put into core tubes for transport back to labs at Brigham Young University in Utah. But first, Koutnik measured the core's length, diameter and weight. The traverse was the first of two field campaigns to study snow accumulation on the West Antarctic Ice Sheet and tie the information back to larger-scale data collected from satellites (photo credit: NASA/Lora Koenig). The temperature at which the ice originally formed can be obtained from an interpretation of the measured ratio of the **stable isotopes** of oxygen in the molecules of water forming the ice. The atmospheric gas composition is taken from air bubbles trapped in the ice at the time of formation. From these data, scientists have gathered a set of reliable data that track atmospheric temperature and gas concentrations that dates back 800,000 years. These data helped scientists come to the conclusion that the Earth's temperature and greenhouse gas concentrations are directly correlated to one another. During the ice age 650,000 years ago, the Earth was experiencing depressed temperature and atmospheric CO2 concentrations below 200 **parts per million** (ppm). We can also see from the data below, that CO2 concentrations can be naturally elevated to as high as 300 ppm,



correlating with increased temperatures. These estimates of the Earth's changing CO2 concentration (top) and Antarctic temperature (bottom) are based on analysis of ice core data extending back 800,000 years. Until the past century, natural factors caused atmospheric CO2 concentrations to vary within a range of about 180 to 300 ppm. Warmer periods coincide with periods of relatively high CO2 concentrations. NOTE: The past century's temperature changes and rapid CO2 rise (to 400 ppm in 2015) are not shown here (Source: Based on data appearing in NRC (2010)).

The 100,000 year major cycle of the ice ages and some variations within the cycles agree very well with predicted periodic relationships between the Earth's orbit around the sun, generally referred to as the **Milankovitch cycles**. Milankovitch cycles describe the very slight "wobbles" that occur in the Earth's tilt and path as it moves around the sun. The Earth is always slightly tilted on its axis with respect to the sun. The angle of this tilt, however, changes periodically, varying from about 22° to about 25°. A less severe tilt will cause milder summers and winters close to the poles, preventing full summer ice melt in the northern- and southernmost regions, and allowing for a buildup of ice from year to year.

The path through which the Earth travels on its journey around the sun also changes from a more circular to a more elongated shape. Again, a round orbit will cause milder summers and winters close to the poles. These are very long term changes, and the results of the Milankovitch cycles can be observed in the changes in temperature and atmospheric CO2 concentration shown in Figure 6.8. The climate change event that scientists are currently documenting is occurring much more rapidly than could be explained by Milankovitch cycles. Therefore, scientists agree that the cause of our currently changing climate is due to human impacts and not natural forces.

Greenhouse gases

We will be covering the four major categories of greenhouse gases that have been impacted by humans the most.

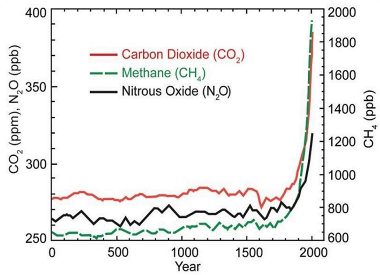
- Carbon dioxide, CO_2
- Methane, CH_4
- Nitrous oxide, N_2O
- Synthetic fluorinated gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)

Carbon dioxide (CO_2) is the greenhouse gas responsible for most of the human-caused climate change in our atmosphere. It has the highest concentration in the atmosphere of any of the greenhouse gases that we'll discuss here. Remember that CO_2 is a direct product of both combustion and cellular respiration, causing it to be produced in great quantities both naturally and anthropogenically. Any time biomass or fossil fuels are burned, CO_2 is released. Major anthropogenic sources include: electricity production from coal-fired and natural gas power plants, transportation, and industry. To get an idea of how CO_2 concentration has changed over time, watch this video compiled by the National Oceanic and Atmospheric Administration (NOAA): http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html. This video contains atmospheric CO_2 concentrations measured directly, dating back to 1958, as well as atmospheric CO_2 concentrations measured indirectly from ice core data, dating back to 800,000 BCE. By 1990, a quantity of over seven billion tons of carbon (equivalent to 26 billion tons of carbon dioxide when the weight of the oxygen atoms are also considered) was being emitted into the atmosphere every year, much of it from industrialized nations. Similar to the action of the naturally existing greenhouse gases, any additional greenhouse gases leads to an increase in the surface temperature of the Earth.

While CO_2 is produced by aerobic cellular respiration, gases such as CH_4 and N_2O are often the products of anaerobic metabolisms. Agriculture is a major contributor to CH_4 emissions. In addition to anaerobic bacteria, methane is also a significant component of natural gas, and is commonly emitted through the mining and use of natural gas and petroleum, in addition to coal mining. Finally, **landfills** contribute significantly to CH_4 emissions, as the waste put into the landfill largely undergoes anaerobic decomposition as it is buried under many layers of trash and soil. Natural sources of CH_4 include swamps and wetlands, and volcanoes.

The vast majority of N_2O production by humans comes from agricultural land management. While some N_2O is naturally emitted to the atmosphere from soil as part of the nitrogen cycle, human changes in land management, largely due to agricultural practices, have greatly increased N_2O emissions. Some N_2O is also emitted from transportation and industry.

Due to their relatively high concentrations in the atmosphere compared to synthetic gases, CO_2, CH_4, and N_2O, are responsible for most of the human-caused global climate change over the past century. The figure at right shows the increases in all three gases following the industrial revolution. Overall it shows an increase in greenhouse gas concentrations in the atmosphere over the last 2,000 years. Increases in concentrations of these gases since 1750 are due to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion



(ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air (Source: USGCRP (2009)). Ice core data (earlier figure) shows us that the atmospheric CO2 concentration never exceeded 300 ppm before the industrial revolution. As of early 2015, the current atmospheric CO2 concentration is 400 ppm. Comparing these figures, what is likely to happen to global temperature following this unprecedented rise in greenhouse gas levels?

One class of greenhouse gas chemicals that has no natural sources is the fluorinated gases. These include HFCs, PFCs, and SF6, among others. Because these are synthetic chemicals that are only created by humans, these gases were essentially non-existent before the industrial revolution. These synthetic gases are used for a wide variety of applications, from refrigerants to semiconductor manufacturing, and propellants to fire retardants. They tend to have a long lifetime in the atmosphere, as seen in the table below. Some of these chemicals, as well as the older **chlorofluorocarbons** (CFCs), have been phased out by international environmental legislation under the Montreal Protocol. Due to their long lifespan, many of these now-banned CFCs remain in the atmosphere. Newer chemical replacements, such as HFCs, provide many of the same industrial applications, but unfortunately have their own environmental consequences.

Just as greenhouse gases differ in their sources and their residence time in the atmosphere, they also differ in their ability to produce the greenhouse effect. This is measured by the **global warming potential**, or GWP, of each greenhouse gas. The GWP of a greenhouse gas is based on its ability to absorb and scatter energy, as well as its lifetime in the atmosphere. Since CO_2 is the most prevalent greenhouse gas, all other greenhouse gases are measured relative to it. As the reference point, CO_2 always has a GWP of 1. Note the very high GWP values of the synthetic fluorinated gases in the table below. This is largely due to their very long residence time in the atmosphere. Also note the higher GWP values for CH_4 and N_2O compared to CO_2.

Comparison of common greenhouse gases in the atmosphere. Data from US EPA. For more information: http://epa.gov/climatechange/ghgemissions/gases.html

Greenhouse gas	Chemical formula or abbreviation	Lifetime in atmosphere	Global warming potential (100-year)
Carbon dioxide	CO_2	Variable	1
Methane	CH_4	12 years	28-36
Nitrous oxide	N_2O	114 years	298
Hydrofluorocarbons	Abbreviation: HFCs	1-270 years	12-14,800
Perfluorocarbons	Abbreviation: PFCs	2,600-50,000 years	7,390
Sulfur hexafluoride	SF_6	3,200 years	22,800

Other climate influencers

In addition to greenhouse gases, other manmade changes may be forcing climate change. Increases in near surface ozone from internal combustion engines, aerosols such as carbon black, mineral dust and aviation-induced exhaust are acting to raise the surface temperature. This primarily occurs due to a decrease in the **albedo** of light-colored surfaces by the darker-colored carbon black, soot, dust, or particulate matter. As you know, it is more comfortable to wear a white shirt on a hot summer day than a black shirt. Why is this? Because the lighter-colored material bounces more solar radiation back toward space than the darker-colored material does, allowing it to stay cooler. The darker-colored material absorbs more solar radiation, increasing its temperature. Just as the white shirt has a higher albedo than the black shirt, light-colored objects in nature (such as snow) have a higher albedo than dark-colored objects (such as soot or dust). As humans increase the amount of carbon black, soot, dust, and particulates in the atmosphere, we decrease the albedo of light-colored surfaces, causing them to absorb more solar radiation and become warmer than they would without human influence.

Find out more in this article from the National Oceanic and Atmospheric Administration

Information in this chapter includes materials taken directly from and adapted from https://climate.nasa.gov/vital-signs/

The chapter also contains substantial content from Zehnder, Caralyn; Manoylov, Kalina; Mutiti, Samuel; Mutiti, Christine; VandeVoort, Allison; and Bennett, Donna, "Introduction to Environmental Science: 2nd Edition" (2018). *Biological Sciences Open Textbooks*. 4. You can download the original for free at https://oer.galileo.usg.edu/biology-textbooks/4/. https://oer.galileo.usg.edu/biology-textbooks/4. That resource includes materials modified from OpenStax. Download for free at http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3.

3. Evolution

All organisms are products of evolution adapted to their environment. On the left, Saguaro (*Carnegiea gigantea*) can soak up 750 liters of water in a single rain storm, enabling these cacti to survive the dry conditions of the Sonora desert in Mexico and the Southwestern United States. On the right, the Andean semiaquatic lizard (*Potamites montanicola*) discovered in Peru in 2010 lives between 1,570 to 2,100 meters in elevation, and, unlike most lizards, is nocturnal and swims. Scientists still do not know how these cold-blood animals are able to move in the cold (10 to 15°C) temperatures of the Andean night. (credit a: modification of work by Gentry George, U.S. Fish and Wildlife Service; credit b: modification of work by Germán Chávez and Diego Vásquez, *ZooKeys*)

The theory of **evolution** is the unifying theory of biology, meaning it is the framework within which biologists ask questions about the living world. Because ecology is a branch of biology, understanding evolution is crucial for understanding ecology. In Chapter 1, we talked about scientific theories and described some theories as fundamental theories. Evolution is one of these fundamental theories because of its power to explain a lot about our world and its support from repeated observations and experiments. Its power is that it provides direction for predictions about living things that are borne out in ongoing experiments. The Ukrainian-born American geneticist Theodosius Dobzhansky famously wrote that "nothing makes sense in biology except in the light of evolution."1 He meant that the tenet that all life has evolved and diversified from a common ancestor is the foundation from which we approach all questions in biology. Evolution is a change in the inherited characteristics (what we now know is the genetic makeup) of a species through generations. Many people confuse **natural selection** (explained below) and human evolution with the overall theory of evolution. These two concepts are certainly part of our understanding of evolution, but do not encompass all of the theory of evolution.

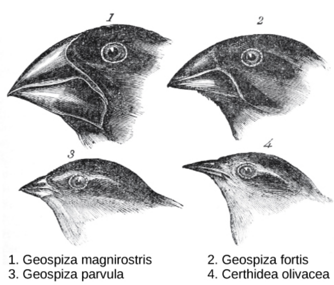
Development of the Theory of Evolution

Evolution by natural selection describes a mechanism for how species change over time. Scientists, philosophers, researchers, and others had made suggestions and debated this topic well before Darwin began to explore this idea. Classical Greek philosopher Plato emphasized in his writings that species were static and unchanging, yet there were also ancient Greeks who expressed evolutionary ideas. In the eighteenth century, naturalist Georges-Louis Leclerc Comte de Buffon reintroduced ideas about the evolution of animals and observed that various geographic regions have different plant and animal populations, even when the environments are similar. Some at this time also accepted that there were extinct species.

Also during the eighteenth century, James Hutton, a Scottish geologist and naturalist, proposed that geological change occurred gradually by accumulating small changes from processes operating like they are today over long periods of time, a theory called uniformitarianism. This contrasted with the predominant view that the planet's geology was a consequence of catastrophic events occurring during a relatively brief past, a theory called catastrophism. For example, from a uniformitarian viewpoint, the Grand Canyon was formed over millions of years from the slow erosion of sediment by the Colorado River. From the catastrophism perspective, the Grand Canyon formed from a single large event, unlike events we see today. Nineteenth century geologist Charles Lyell popularized Hutton's view, which is accepted today. A friend to Darwin. Lyell's ideas were influential on Darwin's thinking: Lyell's notion of the greater age of Earth gave more time for gradual change in species, and the process of change provided an analogy for this change. In the early nineteenth century, Jean-Baptiste Lamarck published a book that detailed a mechanism for evolutionary change. Lamarck proposed that changes in an individual organism during its lifetime were passed on to its offspring in a theory of inheritance of acquired characteristics. The classic example from Lamarck's theory is that giraffes repeatedly stretched their necks to reach higher leaves on trees. As the giraffe stretched its neck, its neck got longer and this longer neck was passed on to future generations. While Lamarck's theory was discredited, in recent years, the study of epigenetics has demonstrated that behaviors and the environment of an individual can affect the expression of that individual's DNA with the possibility that these changes can be passed on through generations. You can read more at this website with information about epigenetics.

Charles Darwin and Natural Selection

In the mid-nineteenth century, two naturalists, Charles Darwin and Alfred Russel Wallace, independently conceived and described natural selection as a mechanism for evolution. Importantly, each naturalist spent time exploring the natural world on expeditions to the tropics. From 1831 to 1836, Darwin traveled around the world on *H.M.S. Beagle*, including stops in South America, Australia, and the southern tip of Africa. Wallace traveled to Brazil to collect insects in the Amazon rainforest from 1848 to 1852 and to the Malay Archipelago from 1854 to 1862. Darwin's journey, like Wallace's later journeys to the Malay Archipelago, included stops at several island chains, the last being the Galápagos Islands west of Ecuador. On these islands, Darwin observed species of organisms on different islands that were clearly similar, yet had distinct differences. For example, the ground finches inhabiting the Galápagos Islands comprised several species with a unique beak shape. The species on the islands had a graded series of beak sizes and shapes with very small differences between the most similar. He observed that these finches closely resembled another finch species on the South American mainland. Darwin imagined that the island species might be species modified from one of the original mainland species. Upon further study, he realized that each finch’s varied beaks helped the birds acquire a specific type of food. For example, seed-eating finches had stronger, thicker beaks for breaking seeds, and insect-eating finches had spear-like beaks for stabbing their prey.



Finches from Galapagos Archipelago

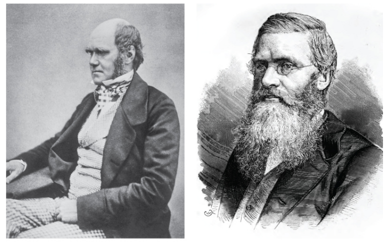
Darwin observed that beak shape varies among finch species. He postulated that ancestral species’ beaks had adapted over time to equip the finches to acquire different food sources.

Wallace and Darwin both observed similar patterns in other organisms and they independently developed the same explanation for how and why such changes could take place. Darwin called this mechanism natural selection. Natural selection is the more prolific reproduction of individuals with favorable traits that survive environmental change because of those traits. This leads to evolutionary change. Natural selection is sometimes referred to as “survival of the fittest,” but this phrase does not accurately represent natural selection. Natural selection requires that an individual not only survive, but also reproduce and that the characteristics that increased the likelihood of that individual surviving and reproducing are passed on to the next generation.

For example, Darwin observed a population of giant tortoises in the Galápagos Archipelago to have longer necks than those that lived on other islands with dry lowlands. These tortoises were “selected” because they could reach more leaves and access more food than those with short necks. In times of drought when fewer leaves would be available, those that could reach more leaves had a better chance to eat and survive than those that couldn't reach the food source. Consequently, long-necked tortoises would be more likely to be reproductively successful and pass the long-necked trait to their offspring. Over time, only long-necked tortoises would be present in the population.

Natural selection, Darwin argued, was an inevitable outcome of three principles that operated in nature. First, most characteristics of organisms are inherited, or passed from parent to offspring. Although no one, including Darwin and Wallace, knew how this happened at the time, it was a common understanding. Second, more offspring are produced than are able to survive, so resources for survival and reproduction are limited. The capacity for reproduction in all organisms outstrips the availability of resources to support their numbers. Thus, there is competition for those resources in each generation. Both Darwin and Wallace's understanding of this principle came from reading economist Thomas Malthus' essay that explained this principle in relation to human populations. Third, offspring vary among each other in regard to their characteristics and those variations are inherited. Darwin and Wallace reasoned that offspring with inherited characteristics which allow them to best compete for limited resources will survive and have more offspring than those individuals with variations that are less able to compete. Because characteristics are inherited, these traits will be better represented in the next generation. This will lead to change in populations over generations in a process that Darwin called descent with modification. Ultimately, natural selection leads to greater **adaptation** of the population to its local environment. It is the only mechanism known for adaptive evolution.

In 1858, Darwin and Wallace (see picture at right) presented papers at the Linnean Society in London that discussed the idea of natural selection. The following year Darwin's book, *On the Origin of Species*, was published. His book outlined in considerable detail his arguments for evolution by natural selection.



(a) (b)

It is difficult and time-consuming to document and present examples of evolution by natural selection. The Galápagos finches are an excellent example. Peter and Rosemary Grant and their colleagues have studied Galápagos finch populations every year since 1976 and have provided important evidence of natural selection. The Grants found changes from one generation to the next in beak shape distribution with the medium ground finch on the Galápagos island of Daphne Major. The birds have inherited a variation in their bill shape with some having wide deep bills and others having thinner bills. During a period in which rainfall was higher than normal because of an El Niño, there was a lack of large hard seeds that the large-billed birds ate; however, there was an abundance of the small soft seeds which the small-billed birds ate. Therefore, the small-billed birds were able to survive and reproduce. In the years following this El Niño, the Grants measured beak sizes in the population and found that the average bill size was smaller. Since bill size is an inherited trait, parents with smaller bills had more offspring and the bill evolved into a much smaller size. As conditions improved in 1987 and larger seeds became more available, the trend toward smaller average bill size ceased. The Grant's were able to document evolution by natural selection on a much shorter time scale than many scientists have been able to demonstrate.

Processes and Patterns of Evolution

Natural selection can only take place if there is variation, or differences, among individuals in a population. Importantly, these differences must have some genetic basis; otherwise, the selection will not lead to change in the next generation. This is critical because nongenetic reasons can also cause variation among individuals such as an individual's height because of better nutrition rather than different genes.

Before proceeding, if you need a quick review of basic genetics, take a break to watch this video about alleles and genes.

Genetic diversity in a population comes from two main mechanisms: mutation and sexual reproduction. Mutation, a change in DNA, is the ultimate source of new genetic variation in any population. The genetic changes that mutation causes can have one of three outcomes on the phenotype, the observable characteristics of the organism.

- 1) A mutation affects the organism's phenotype in a way that gives it reduced fitness—lower likelihood of survival or fewer offspring.
- 2) A mutation may produce a phenotype with a beneficial effect on fitness.
- 3) Many mutations, called neutral mutations, will also have no effect on the phenotype's fitness.

Mutations also vary in how large their impact is on the organism's fitness that expresses them in their phenotype, from a small effect to a great effect. Sexual reproduction also leads to genetic diversity: when two parents reproduce, unique combinations of genetic material assemble to produce the unique characteristics of the offspring. Sexual reproduction, such as pollination of flowers and fertilization of eggs in animals, involves the combination of genetic material from two organisms. In asexual reproduction, a single organism produces offspring, such as the runners from a strawberry plant producing new plants.

We call a heritable trait that helps an organism's survival and reproduction in its present environment an adaptation. Scientists describe groups of organisms adapting to their environment when a genetic variation occurs over time that increases or maintains the population's "fit" to its environment. A platypus's webbed feet are an adaptation for swimming. A snow leopard's thick fur is an adaptation for living in the cold. A cheetah's fast speed is an adaptation for catching prey.

Whether or not a trait is favorable depends on the current environmental conditions. The same traits are not always selected because environmental conditions can change. For example, consider a plant species that grew in a moist climate and did not need to conserve water. Large leaves were selected because they allowed the plant to obtain more energy from the sun and produce more offspring in the next generation, therefore increasing the overall leaf size of the species. Large leaves require more water to maintain than small leaves, and the moist environment provided favorable conditions to support large leaves. After thousands of years, the climate changed, and the area no longer had excess water. The direction of natural selection shifted so that plants with small leaves were selected because those populations were able to conserve water to survive the new environmental conditions. If the plant does not adapt, the plant may go extinct in that area. A plant, or any organism, cannot choose to adapt because of changing environmental conditions, adaptations can only occur if that characteristic appears in the population.

The evolution of species has resulted in enormous variation in form and function. Sometimes, evolution gives rise to groups of organisms that become tremendously different from each other. We call two species that evolve in diverse directions from a common point divergent evolution. We can see such divergent evolution in the forms of the reproductive organs of flowering plants which share the same basic anatomies; however, they can look very different as a result of selection in different physical environments and adaptation to different kinds of pollinators.

(a) (b)

The flowering plants shown above evolved from a common ancestor. Notice that the dense blazing star (*Liatrus spicata*) on the left and the purple coneflower (*Echinacea purpurea*) on the right vary in appearance, yet both share a similar basic morphology. (credit left: a modification of work by Drew Avery; credit right: modification of work by Cory Zanker)

In other cases, similar phenotypes evolve independently in distantly related species. For example, flight has evolved in both bats and insects, and they both have structures we refer to as wings, which are adaptations to flight. However, bat and insect wings have evolved from very different original structures. We call this phenomenon **convergent evolution**, where similar traits evolve independently in species that do not share a common ancestry. The two species came to the same function, flying, but did so separately from each other.

These physical changes occur over enormous time spans and help explain how evolution occurs. Natural selection acts on individual organisms, which can then shape an entire species. Although natural selection may work in a single generation on an individual, it takes many generations, and therefore often thousands or even millions of years, for an entire species to evolve. It is over these large time spans that life on earth has changed and continues to change.

The Modern Synthesis

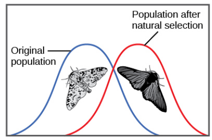
The mechanisms of inheritance, genetics, were not understood at the time Darwin and Wallace were developing their idea of natural selection. This lack of understanding was a stumbling block to comprehending many aspects of evolution. In fact, blending inheritance was the predominant (and incorrect) genetic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

Population Genetics

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

Until now, we have defined evolution as a change in the characteristics of a population of organisms, but behind that phenotypic change is genetic change. In population genetic terms, evolution is defined as a change in the frequency of an allele in a population. Each human has 23 pairs of chromosomes made of strands of DNA. In one of these pairs, each chromosome contains a gene for blood type, the ABO gene. This gene might be any of the three alleles of the ABO gene. Using the ABO system as an example, the frequency of one of the alleles, IA, is the number of copies of that allele divided by all the copies of the ABO gene in the population. For example, a study in Jordan found a frequency of IA to be 26.1 percent.2 The IB, I0 alleles made up 13.4 percent and 60.5 percent of the alleles respectively, and all of the frequencies add up to 100 percent. A change in this frequency over time would constitute evolution in the population.

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



Light-colored peppered moths are better camouflaged against a pristine environment; likewise, dark-colored peppered moths are better camouflaged against a sooty environment. Thus, as the Industrial Revolution progressed in nineteenth-century England, the color of the moth population shifted from light to dark.

In the early twentieth century, English mathematician Godfrey Hardy and German physician Wilhelm Weinberg independently provided an explanation for a somewhat counterintuitive concept. Hardy’s original explanation was in response to a misunderstanding as to why a “dominant” allele, one that masks a recessive allele, should not increase in frequency in a population until it eliminated all the other alleles. The question resulted from a common confusion about what “dominant” means, but it forced Hardy, who was not even a biologist, to point out that if there are no factors that affect an allele frequency those frequencies will remain constant from one generation to the next. This principle is now known as the Hardy-Weinberg equilibrium. The theory states that a population’s allele and genotype frequencies are inherently stable—unless some kind of evolutionary force is acting on the population, the population would carry the same alleles in the same proportions generation after generation. Individuals would, as a whole, look essentially the same and this would be unrelated to whether the alleles were dominant or recessive. The four most important evolutionary forces, which will disrupt the equilibrium, are **natural selection**, **mutation**, **genetic drift**, and **migration** into or out of a population.

Natural Selection

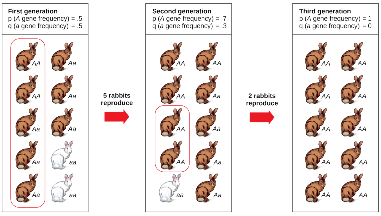
Natural selection has already been discussed. Alleles are expressed in a phenotype. Depending on the environmental conditions, the phenotype confers an advantage or disadvantage to the individual with the phenotype relative to the other phenotypes in the population. If it is an advantage, then that individual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

Mutation

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

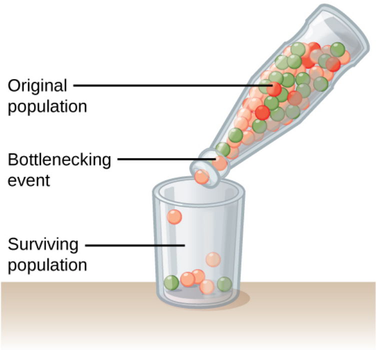
Genetic Drift

Another way a population's allele frequencies can change is genetic drift, which is simply the effect of chance and is most important in small populations. This process is illustrated in the image at right. Genetic drift occurs because the alleles in an offspring generation are a random sample of the alleles in the parent generation. Alleles may or may not make it into the next generation due to chance



events. For example, consider the simplified example of a population of 10 rabbits in the figure. The dominant allele (A) leads to brown coloration and the recessive allele (a) leads to white coloration. Therefore, any rabbit with an A gene will be brown and only rabbits with two a genes will be white. In the first generation the frequency of the dominant allele (p) equals the frequency of the recessive allele (q). The sum of these two frequencies must add up to one, so each frequency is 0.5. We can find out how many alleles of each type there are by multiplying the frequency (0.5) by the total number of genes (two genes for fur color in each rabbit multiplied by ten rabbits gives 20 genes or 10 of each allele). Imagine a tree falls, killing half of the rabbits at random. In this scenario, the only two white rabbits in the population were killed by chance and therefore unable to reproduce. The remaining five rabbits reproduce to create 10 new rabbits in the second generation, but the frequency of the a allele is now only 0.3. In this generation, another tree falls and kills 8 rabbits, leaving only two rabbits to reproduce. Both happen to have two copies of the dominant allele (A) and so by the third generation, the recessive allele (a) is lost. The two falling trees is obviously improbable, but the key for genetic drift is that the loss of the allele is due to chance. If the white rabbits were easier for predators to see and therefore killed at a greater rate decreasing the frequency of the a allele in future generations, that would be an example of natural selection, not genetic drift.

In our example above, a natural or human-caused event randomly killed a large portion of the population. This is known as a **genetic bottleneck** and can result in a large portion of the genome suddenly being wiped out. This concept is illustrated on the right. In one fell swoop, the genetic structure of the survivors becomes the genetic structure of the entire population, which may be very different from the pre-disaster population. In particular, rare alleles are likely to be lost in a genetic bottleneck. The disaster must be one that kills for reasons unrelated to the organism's traits, such as a hurricane or lava flow. A mass killing caused by unusually cold temperatures at night, is likely to affect individuals differently depending on the alleles they possess that confer cold hardiness.

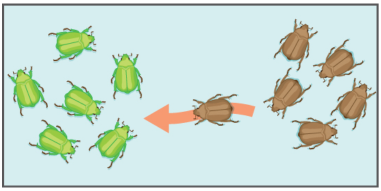


Another scenario in which populations might experience a strong influence of **genetic drift** is if some portion of the population leaves to start a new population in a new location, or if a population gets divided by a physical barrier of some kind. In this situation, those individuals are unlikely to be representative of the entire population which results in the founder effect. The founder effect occurs when the genetic structure matches that of the new population's founding fathers and mothers. The founder effect is believed to have been a key factor in the genetic history of the Afrikaner population of Dutch settlers in South Africa, as evidenced by mutations that are common in Afrikaners but rare in most other populations. This is likely due to a higher-than-normal proportion of the founding colonists, which were a small sample of the original population, carrying these mutations. As a result, the population expresses unusually high incidences of Huntington's disease (HD) and Fanconi anemia (FA), a genetic disorder known to cause bone marrow and congenital abnormalities, and even cancer.3

CONCEPTS IN ACTION

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

Gene Flow and Migration



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

Species and the Ability to Reproduce

Although all life on earth shares various genetic similarities, only certain organisms combine genetic information by sexual reproduction and have offspring that can then successfully reproduce. Scientists call such organisms members of the same biological species.

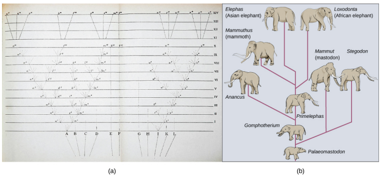
A **species** is a group of individual organisms that interbreed and produce fertile, viable offspring. According to this definition, one species is distinguished from another when, in nature, it is not possible for matings between individuals from each species to produce fertile offspring. In reality, the definition of a species is not so clean-cut. For example, some species, like the carrion crow and the hooded crow occasionally interbreed and produce viable offspring, called hybrids. While most hybrids are sterile, the combined offspring of a carrion crow and a hooded crow is often fertile. Scientists now consider these birds evolving species, descendants of a common ancestor that are becoming distinct species. Group of organisms in close proximity in space or time can also challenge this definition of species by partial interbreeding.

For example, many, but not all, of the subspecies of *Ensatina* salamanders can interbreed, and all of the subspecies can interbreed with some of the other subspecies. Like the crows, scientists consider this evidence of evolution in action. Finally, for organisms that reproduce asexually, the biological definition of species is inapplicable and species are generally defined by genetic similarity.

Populations of species share a gene pool: a collection of all the gene variants in the species. Again, the basis to any changes in a group or population of organisms must be genetic for this is the only way to share and pass on traits. When variations occur within a species, they can only pass to the next generation along two main pathways: asexual reproduction or sexual reproduction. The change will pass on asexually simply if the reproducing cell possesses the changed trait. For the changed trait to pass on by sexual reproduction, a gamete, such as a sperm or egg cell, must possess the changed trait. In other words, sexually-reproducing organisms can experience several genetic changes in their body cells, but if these changes do not occur in a sperm or egg cell, the changed trait will never reach the next generation. Only heritable traits can evolve. Therefore, reproduction plays a paramount role for genetic change to take root in a population or species. In short, organisms must be able to reproduce with each other to pass new traits to offspring.

Speciation

Given the extraordinary diversity of life on the planet there must be mechanisms for **speciation**: the formation of two species from one original species. Darwin envisioned this process as a branching event and diagrammed the process in the only illustration in *On the Origin of Species* (the left panel of the image at right). Compare this illustration to the diagram of elephant evolution (the right panel of the image at right), which shows that as one



species changes over time, it branches to form more than one new species, repeatedly, as long as the population survives or until the organism becomes extinct. Darwin's diagram shows many similarities to phylogenetic charts that today illustrate the relationships of species.

For speciation to occur, two new populations must form from one original population and they must evolve in such a way that it becomes impossible for individuals from the two new populations to interbreed. Biologists have proposed mechanisms by which this could occur that fall into two broad categories. **Allopatric speciation** (allo- = "other"; -patric = "homeland") involves geographic separation of populations from a parent species and subsequent evolution. **Sympatric speciation** (sym- = "same"; -patric = "homeland") involves speciation occurring within a parent species remaining in one location.

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

Allopatric Speciation

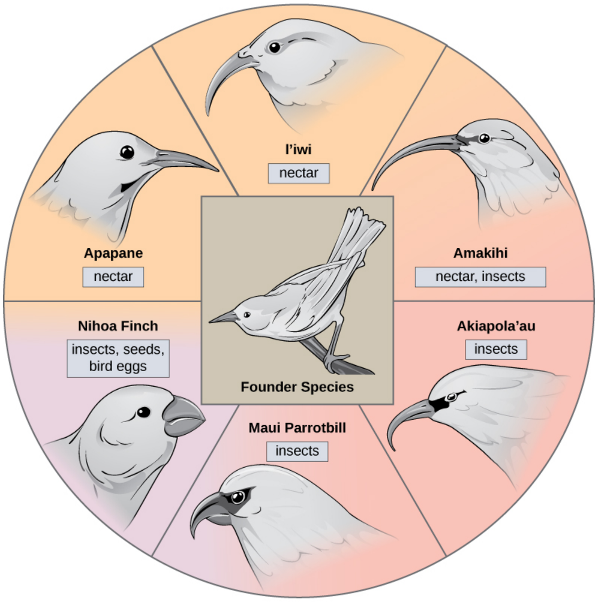
A geographically continuous population has a gene pool that is relatively homogeneous. Gene flow, the movement of alleles across a species' range, is relatively free because individuals can move and then mate with individuals in their new location. Thus, an allele's frequency at one end of a distribution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

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

Additionally, scientists have found that the further the distance between two groups that once were the same species, the more likely it is that speciation will occur. This seems logical because as the distance increases, the various environmental factors would likely have less in common than locations in close proximity. This variation will not lead to new species unless some barrier to successful reproduction also develops.

Adaptive Radiation

In some cases, a population of one species disperses throughout an area, and each finds a distinct niche or isolated habitat. Over time, the varied demands of their new lifestyles lead to multiple speciation events originating from a single species. We call this adaptive radiation because many adaptations evolve from a single point of origin; thus, causing the species to radiate into several new ones. Island archipelagos like the Hawaiian Islands provide an ideal context for adaptive radiation events because water surrounds each island which leads to geographical isolation for many organisms. The Hawaiian honeycreeper illustrates one example of adaptive radiation. From a single species, the founder species, numerous species have evolved, including the six shown below.



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

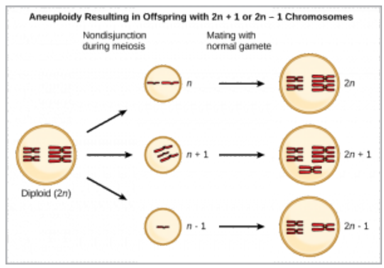
LINK TO LEARNING

Watch this video to see how scientists use evidence to understand how birds evolved.

Sympatric Speciation

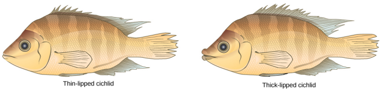
Can divergence occur if no physical barriers are in place to separate individuals who continue to live and reproduce in the same habitat? The answer is yes. We call the process of speciation within the same space sympatric. The prefix "sym" means same, so "sympatric" means "same homeland" in contrast to "allopatric" meaning "other homeland." Scientists have proposed and studied many mechanisms.

One form of sympatric speciation can begin with a serious chromosomal error during cell division. In a normal cell division event, chromosomes replicate, pair up, and then separate so that each new cell has the same number of chromosomes. However, sometimes the pairs separate and the end cell product has too many or too few individual chromosomes in a condition that we call **aneuploidy**. Aneuploidy results when the gametes have too many or too few chromosomes due to nondisjunction during meiosis. In the example at right, the resulting offspring will have $2n$+1 or $2n$-1 chromosomes. This individual often cannot sexually reproduce with other members of the same species, but may be able to self-pollinate, reproduce asexually or reproduce with other individuals from the same species with aneuploidy. In addition, an organisms with aneuploidy can sometimes reproduce viable offspring with an organism of a different species. This type of process created the cultivated form of wheat. This type of speciation is far more common in plant species than in animal species.



Habitat Influence on Speciation

Sympatric speciation may also take place in ways other than polyploidy. For example, consider a fish species that lives in a lake. As the population grows, competition for food increases. Under pressure to find food, suppose that a group of these fish had the genetic flexibility to discover and feed off another resource that other fish did not use. What if this new food source was located at a different depth of the lake? Over time, those feeding on the second food source would interact more with each other than the other fish; therefore, they would breed together as well. Offspring of these fish would likely behave as their parents: feeding and living in the same area and keeping separate from the original population. If this group of fish continued to remain separate from the first population, eventually sympatric speciation might occur as more genetic differences accumulated between them.



This scenario does play out in nature, as do others that lead to reproductive isolation. One such place is Lake Victoria in Africa, famous for its sympatric speciation of cichlid fish. Researchers have found hundreds of sympatric speciation events in these fish, which have not only happened in great number, but also over a short period of time. The figure on the left shows this type of speciation among a cichlid fish population in Nicaragua. Lake Apoyeque, a crater lake, is 1800 years old, but genetic evidence indicates that a single population of cichlid fish populated the lake only 100 years ago. Nevertheless, two populations with distinct morphologies and diets now exist in the lake, and scientists believe these populations may be in an early stage of speciation.

Reproductive Isolation

Given enough time, the genetic and phenotypic divergence between populations will affect characters that influence reproduction: if individuals of the two populations were brought together, mating would be less likely, but if mating occurred, offspring would be nonviable or infertile. For organisms that reproduce sexually, this reproductive isolation is necessary to maintain distinct species. Many types of diverging characteristics may affect the reproductive isolation, the ability to interbreed, of the two populations.

Reproductive isolation can take place in a variety of ways. Scientists organize them into two groups: **prezygotic barriers** and **postzygotic barriers**. Recall that a zygote is a fertilized egg: the first cell of an organism's development that reproduces sexually.

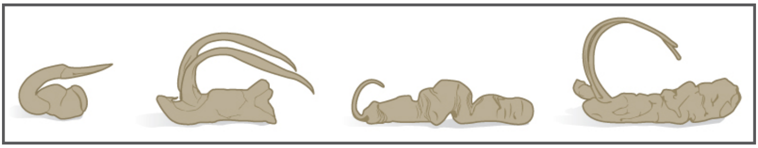
Therefore, a prezygotic barrier is a mechanism that blocks reproduction from taking place. This includes barriers that prevent fertilization when organisms attempt reproduction. A postzygotic barrier occurs after zygote formation. This includes organisms that don't survive the embryonic stage and those that are born sterile.

Some types of prezygotic barriers prevent reproduction entirely. Many organisms only reproduce at certain times of the year, often just annually. Differences in breeding schedules, which we call **temporal isolation**, can act as a form of **reproductive isolation**. For example, two frog species at right inhabit the same area, but one (*Rana aurora*) reproduces from January to March; whereas, the other (*Rana boylii*) reproduces from March to May (Photo credits left: modification of work by Mark R. Jennings, USFWS; right: modification of work by Alessandro Catenazzi).

(a) (b)

Behavioral isolation occurs when the presence or absence of a specific behavior prevents reproduction. For example, male fireflies use specific light patterns to attract females. Various firefly species display their lights differently. If a male of one species tried to attract the female of another, she would not recognize the light pattern and would not mate with the male.

Other prezygotic barriers work when differences in their gamete cells (eggs and sperm) prevent fertilization from taking place. We call this a **gametic barrier**. Similarly, in some cases closely related organisms try to mate, but their reproductive structures simply do not fit together. For example, damselfly males of different species have differently shaped reproductive organs as shown in the image below. If one species tries to mate with the female of another, their body parts simply do not fit together. Reproductive organ incompatibility keeps the species reproductively isolated.



In plants, certain structures aimed to attract one type of pollinator simultaneously prevent a different pollinator from accessing the pollen. The tunnel through which an animal must access nectar can vary widely in length and diameter, which prevents the plant from cross-pollinating with a different species. For example, the wide foxglove flower (left) is adapted for pollination by bees, while the long, tube-shaped trumpet creeper flower (right) is adapted for pollination by hummingbirds.

(a) Honeybee drinking nectar from a foxglove flower

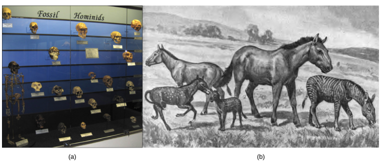
(b) Ruby-throated hummingbird drinking nectar from a trumpet creeper flower

When fertilization takes place and a zygote forms, postzygotic barriers can prevent reproduction. Hybrid individuals in many cases cannot form normally and simply do not survive past the embryonic stages. We call this hybrid inviability because the hybrid organisms simply are not viable. In another postzygotic situation, reproduction leads to hybrid birth and growth that is sterile. Therefore, the organisms are unable to reproduce offspring of their own. We call this hybrid sterility.

Evidence of Evolution

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

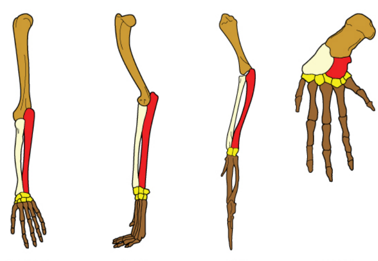
Fossils



Fossils provide solid evidence that organisms from the past are not the same as those today, and fossils show a progression of evolution. Scientists determine the age of fossils and categorize them from all over the world to determine when the organisms lived relative to each other. The resulting fossil record tells the story of the past and shows the evolution of form over millions of years. For example, scientists have recovered highly detailed records showing the evolution of humans and horses. The image to the left shows a display with fossil hominids are arranged from oldest (bottom) to newest (top) on the left. As hominids evolved, the skull's shape changed. The right half of the image shows an artist's rendition of extinct species of the genus *Equus* which reveals that these ancient species resembled the modern horse (*Equus ferus*) but varied in size.

Anatomy and Embryology

Another type of evidence for evolution is the presence of structures in organisms that share the same basic form. For example, as shown to the right, the bones in human, dog, bird, and whale appendages all share the same overall construction resulting from their origin in a common ancestor's appendages. Over time, evolution led to changes in the bones' shapes and sizes different species, but they have maintained



the same overall layout. Scientists call these synonymous parts **homologous structures**.

Some structures exist in organisms that have no apparent function at all and appear to be residual parts from a past common ancestor. We call these unused structures without function **vestigial structures**. Some examples of vestigial structures are wings on flightless birds, leaves on some cacti, and hind leg bones in whales. Not all similarities represent homologous structures. Sometimes, similar characteristics occur because of environmental constraints and not due to a close evolutionary relationship. This is called a **homoplasy**. For example, insects use wings to fly like bats and birds, but the wing structure and embryonic origin are completely different.

This convergence of form in organisms that share similar environments is also evidence of evolution. For example, species of unrelated animals, such as the arctic fox and ptarmigan, living in the arctic region have been selected for seasonal white phenotypes during winter to blend with the snow and ice. These similarities occur not because of common ancestry, but because of similar selection pressures—the benefits of predators not seeing them.

LINK TO LEARNING

Watch this video exploring the bones in the human body.

Biogeography

The geographic distribution of organisms on the planet follows patterns that we can explain best by evolution in conjunction with tectonic plate movement over geological time. Broad groups that evolved before the supercontinent Pangaea broke up (about 200 million years ago) are distributed worldwide. Groups that evolved since the breakup appear uniquely in regions of the planet, such as the unique flora and fauna of northern continents that formed from the supercontinent Laurasia and of the southern continents that formed from the supercontinent Gondwana. The presence of members of the plant family Proteaceae in Australia, southern Africa, and South America was most predominant prior to the southern supercontinent Gondwana breaking up.

Marsupial diversification in Australia and the absence of other mammals reflect Australia's long isolation. Australia has an abundance of endemic species—species found nowhere else—which is typical of islands whose isolation by expanses of water prevents species migration. Over time, these species diverge evolutionarily into new species that look very different from their ancestors that may exist on the mainland. Australia's marsupials, the Galápagos' finches, and many species on the Hawaiian Islands are all unique to their one point of origin, yet they display distant relationships to ancestral species on mainlands. The concept of biogeography is explored further in Chapter 4.

Molecular Biology

Like anatomical structures, the molecular structures of life reflect descent with modification. DNA's universality reflects evidence of a common ancestor for all of life. In general, the relatedness of groups of organisms is reflected in the similarity of their DNA sequences—exactly the pattern that we would expect from descent and diversification from a common ancestor. DNA sequences have also shed light on some of the mechanisms of evolution. For example, it is clear that the evolution of new functions for proteins commonly occurs after gene duplication events that allow freely modifying one copy by mutation, selection, or drift (changes in a population's gene pool resulting from chance), while the second copy continues to produce a functional protein.

Misconceptions of Evolution

Although the theory of evolution generated some controversy when Darwin first proposed it, biologists almost universally accepted it, particularly younger biologists, within 20 years after publication of *On the Origin of Species*. Nevertheless, the theory of evolution is a difficult concept and misconceptions about how it works abound.

LINK TO LEARNING

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

Evolution Is Just a Theory

Critics of the theory of evolution dismiss its importance by purposefully confounding the everyday usage of the word "theory" with the way scientists use the word. As discussed in Chapter 1, a scientific theory is always based on evidence and an accepted scientific theory has has been thoroughly tested and provides an explanation for a set of observations of the natural world. Scientists have a theory of the atom, a theory of gravity, and the theory of relativity, each which describes understood facts about the world. In the same way, the theory of evolution describes facts about the living world. A fundamental theory in science like the theory of evolution has survived significant efforts to discredit it by scientists. In contrast, a "theory" in common vernacular is a word meaning a guess or suggested explanation. When critics of evolution say it is "just a theory," they are implying that there is little evidence supporting it and that it is still in the process of rigorous testing. This is a mischaracterization.

Individuals Evolve

Evolution is the change in a population's genetic composition over time, specifically over generations, resulting from differential reproduction of individuals with certain alleles. Individuals do change over their lifetime, obviously, but this is development and involves changes programmed by the set of genes the individual acquired at birth in coordination with the individual's environment. When thinking about the evolution of a characteristic, it is probably best to think about the change of the average value of the characteristic in the population over time. For example, when natural selection leads to bill-size change in medium ground finches in the Galápagos, this does not mean that individual bills on the finches are changing. If one measures the average bill size among all individuals in the population at one time and then measures them in the population several years later, this average value will be different as a result of evolution. Although some individuals may survive from the first time to the second, they will still have the same bill size; however, there will be many new individuals who contribute to the shift in average bill size.

Evolution Explains the Origin of Life

It is a common misunderstanding that evolution includes an explanation of life's origins. Conversely, some of the theory's critics believe that it cannot possibly explain the origin of life. The theory does not try to explain the origin of life. The theory of evolution explains how populations change over time and how life diversifies the origin of species. It does not shed light on the beginnings of life including the origins of the first cells, which define life.

Organisms Evolve on Purpose

Statements such as "organisms evolve in response to a change in an environment" are quite common, but such statements can lead to two types of misunderstandings. First, do not interpret the statement to mean that individual organisms evolve. The statement is shorthand for "a population evolves in response to a changing environment." However, a second misunderstanding may arise by interpreting the statement to mean that the evolution is somehow intentional. A changed environment results in some individuals in the population, those with particular phenotypes, benefiting and therefore producing proportionately more offspring than other phenotypes. This results in change in the population if the characteristics are genetically determined.

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

In a larger sense, evolution is not goal directed. Species do not become "better" over time. They simply track their changing environment with adaptations that maximize their reproduction in a particular environment at a particular time. Evolution has no goal of making faster, bigger, more complex, or even smarter species, despite the commonness of this kind of language in popular discourse. What characteristics evolve in a species are a function of the variation present and the environment, both of which are constantly changing in a nondirectional way. A trait that fits in one environment at one time may well be fatal at some point in the future. This holds equally well for insect and human species.

You can find more information on evolution at https://evolution.berkeley.edu/evolibrary/article/evo_01.

- **Footnotes**
    - 1Theodosius Dobzhansky. "Biology, Molecular and Organismic." *American Zoologist*4, no. 4 (1964): 449.
    - 2Sahar S. Hanania, Dhia S. Hassawi, and Nidal M. Irshaid, "Allele Frequency and Molecular Genotypes of ABO Blood Group System in a Jordanian Population," *Journal of Medical Sciences*7 (2007): 51-58, doi:10.3923/jms.2007.51.58
    - 3A. J. Tipping et al., "Molecular and Genealogical Evidence for a Founder Effect in Fanconi Anemia Families of the Afrikaner Population of South Africa," PNAS98, no. 10 (2001): 5734-5739, doi: 10.1073/pnas.091402398.

- Content modified from
    - o Authors: Samantha Fowler, Rebecca Roush, James Wise
    - o Publisher/website: OpenStax
    - o Book title: Concepts of Biology
    - o Publication date: Apr 25, 2013

    - o Location: Houston, Texas
    - o Book URL: https://openstax.org/books/concepts-biology/pages/1-introduction

- Access for free at https://openstax.org/books/biology-2e@16.144/pages/1-introduction

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    - Publisher/website: OpenStax
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    - Publication date: Mar 28, 2018
    - Location: Houston, Texas
    - Book URL: https://openstax.org/books/biology-2e@16.144/pages/1-introduction
    - Section URL: https://openstax.org/books/biology-2e@16.144/pages/1-introduction

4. Biogeography and Biomes

Many forces influence the communities of living organisms present in different parts of the biosphere (all of the parts of Earth inhabited by life). The biosphere extends into the atmosphere (several kilometers above Earth) and into the depths of the oceans. Despite its apparent vastness to an individual human, the biosphere occupies only a minute space when compared to the known universe. Many abiotic forces influence where life can exist and the types of organisms found in different parts of the biosphere. The abiotic factors influence the distribution of **biomes**: large areas of land with similar climate, flora, and fauna.

Biogeography

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

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

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

Species distribution patterns are based on biotic and abiotic factors and their influences during the very long periods of time required for species evolution; therefore, early studies of biogeography were closely linked to the emergence of evolutionary thinking in the eighteenth century. Some of the most distinctive assemblages of plants and animals occur in regions that have been physically separated for millions of years by geographic barriers. Biologists estimate that Australia, for example, has between 600,000 and 700,000 species of plants and animals. Approximately 3/4 of living plant and mammal species are endemic species found solely in Australia. A wallaby (*Wallabia bicolor*), on the left in the image below, is a medium-sized member of the kangaroo family that is a pouched mammal, or marsupial (photo credit: (credit: modification of work by Derrick Coetzee;). The echidna (*Tachyglossus aculeatus*), on the right in the image below, is an egg-laying mammal (photo credit: modification of work by Allan Whittome)

(a) (b)

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

Plants can also be specialists or generalists: specialist plants need specific conditions and resources and are often found in limited areas. Endemic species are a specific type of specialists that are found only in specific, often isolated, regions of the Earth, while generalists are found on many regions. Generalists are also able to use a wider range of resources or tolerate a wider range of conditions. Isolated land masses- such as Australia, Hawaii, and Madagascar—often have large numbers of endemic plant species. Some of these plants are endangered due to human activity The forest gardenia (*Gardenia brighamii*), shown on the right, for instance, is endemic to Hawaii; only an estimated 15–20 trees are thought to exist. This tree is listed as federally endangered and is found only in five of the Hawaiian Islands in small populations consisting of a few individual specimens (photo credit: Forest & Kim Starr). Some of the primary factors that control the geographic distributions of species include energy sources, temperature and water.

Energy Sources

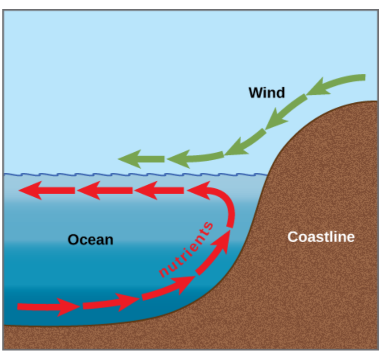
Energy from the sun is captured by green plants, algae, cyanobacteria, and photosynthetic protists. These organisms convert solar energy into the chemical energy needed by all living things. Light availability can be an important force directly affecting the evolution of adaptations in photosynthesizers.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

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

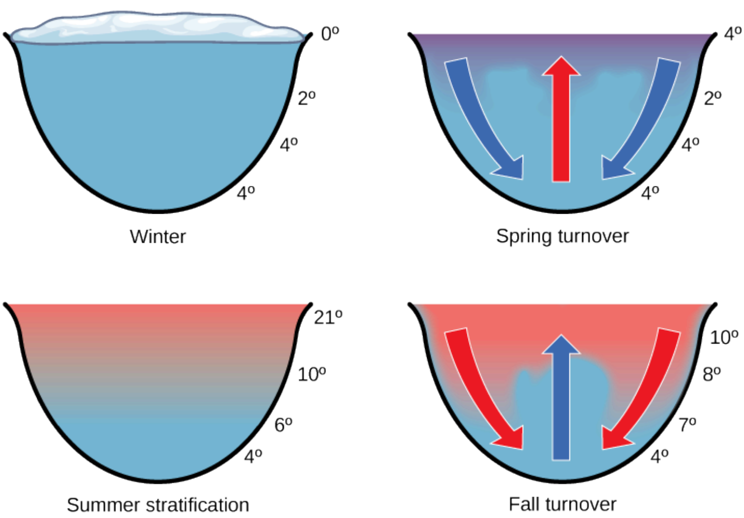
Inorganic Nutrients

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

The availability of nutrients in aquatic systems is also an important factor. Many organisms sink to the bottom of the ocean when they die in the open water; when this occurs, the energy found in that living organism is sequestered for some time unless ocean upwelling occurs.



Ocean upwelling is the rising of deep ocean waters that occurs when prevailing winds blow along surface waters near a coastline. As the wind (green arrows) pushes ocean waters offshore, water from the bottom of the ocean (red arrows) moves up to replace this water. As a result, the nutrients once contained in dead organisms become available for reuse by other living organisms.In freshwater systems, the recycling of nutrients occurs in response to air temperature changes. The nutrients at the bottom of lakes are recycled twice each year: in the spring and fall turnover. The **spring and fall turnover,** shown below, is a seasonal process that recycles nutrients and oxygen from the bottom of a freshwater ecosystem to the top of a body of water. These turnovers are caused by the formation of a thermocline: a layer of water with a temperature that is significantly different from that of the surrounding layers. In wintertime, the surface of lakes found in many northern regions is frozen. However, the water under the ice is slightly warmer, and the water at the bottom of the lake is warmer yet at 4 °C to 5 °C (39.2 °F to 41 °F). Water is densest at 4 °C; therefore, the deepest water is also the densest. The deepest water is oxygen poor because the decomposition of organic material at the bottom of the lake uses up available oxygen that cannot be replaced by means of oxygen diffusion into the water due to the surface ice layer.



In springtime, air temperatures increase and surface ice melts. When the temperature of the surface water begins to reach 4 °C, the water becomes heavier and sinks to the bottom (blue arrows). The water at the bottom of the lake is then displaced by the heavier surface water and rises to the top (red arrow). As that water rises to the top, the sediments and nutrients from the lake bottom are brought along with it. During the summer months, the lake water stratifies, or forms layers, with the warmest water at the lake surface. This makes the layering of the water very stable because the warm surface waters are the least dense and the density increases and the temperature decreases with depth.

As air temperatures drop in the fall, the temperature of the lake water cools to 4 °C; therefore, this causes fall turnover as the heavy cold water sinks and displaces the water at the bottom. The oxygen-rich water at the surface of the lake then moves to the bottom of the lake, while the nutrients at the bottom of the lake rise to the surface. During the winter, the oxygen at the bottom of the lake is used by decomposers and other organisms requiring oxygen, such as fish.

Temperature

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

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

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

Water

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

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

Other Aquatic Factors

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

Other Terrestrial Factors

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

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

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

Abiotic Factors Influencing Plant Growth

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

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

Impacts on biodiversity

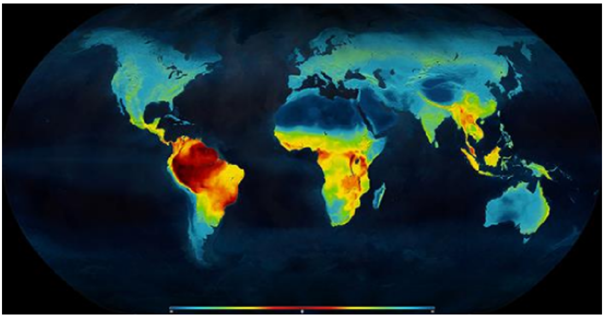
The factors discussed above all affect whether or not an individual species can live in an area and the overall productivity in the area. Biogeography also examines broad patterns in species richness, the number of different species in an area, and three main patterns appear.

The latitudinal diversity gradient

The latitudinal diversity gradient (LDG) is the global pattern of increased species richness in the tropics that decreases moving towards the poles. This patterns is seen for a wide-range of organisms and is a widely accepted pattern in ecology. However, the cause of this pattern is not widely agreed upon. In 2017, Schemske and Mittlebach[1] reviewed the main hypotheses suggested to explain the LDG. Many of these hypotheses had been summarized in a 1966 paper by Eric Pianka[2] The most widely supported theory is that the greater diversity in the tropics is due to a longer time for species to evolve and immigrate in the tropics because the higher latitudes have experienced glacial periods. When Pianka reviewed

1. Schemske, D. W., & Mittelbach, G. G. (2017). "Latitudinal Gradients in Species Diversity": Reflections on Pianka's 1966 Article and a Look Forward. The American naturalist, 189(6), 599–603. https://doi.org/10.1086/691719
2. Pianka, Eric R. 1966. Latitudinal gradients in species diversity: a review of concepts. American Naturalist 100:33–46.

the hypotheses about the LDG, most of them were based on species interactions, but as ecological understanding has improved, most of the more recent hypotheses are based on evolution (Schemske and Mitlebach 2017). Regardless of the cause, the global pattern of increased species richness near the tropics is clear. For example, the map below shows the distribution of vertebrate animals on land with the red color indicating higher species richness and the blue colors representing lower species richness. This figure (CC BY 3.0) is from a research paper by Mannion et al 2104[3] which also presents a theory for evolutionary causes of the LDG.



Mannion et al (2014) categorize the hypothesis about the cause of the LDG as hypotheses that propose that the tropics could have higher diversity because of higher rates of speciation in the tropics, because of lower rates of extinction or because of a combination of the two. On a broader scale, Mannion et al (2014) classify explanations of the LDG as those based on the area of the tropics, the time available for evolution (as discussed above) or the energy

3. Mannion, P. D., Upchurch, P., Benson, R. B., & Goswami, A. (2014). The latitudinal biodiversity gradient through deep time. Trends in ecology & evolution, 29(1), 42–50. https://doi.org/10.1016/j.tree.2013.09.012

available from sunlight and the lower seasonality in the tropics. While agreement about the causes of the LDG does not exist, Mannion et al's (2014) examination of the fossil record indicates that climate (solar energy and low seasonality variability) is a dominant factor.

The elevation diversity gradient

The elevation diversity gradient is a trend towards greater species richness at middle elevations. In some ways, this gradient is not surprising because elevation is often used as a proxy for latitude in research because temperature tends to decrease with higher elevation and latitude. However, the elevational diversity gradient is much less studied.

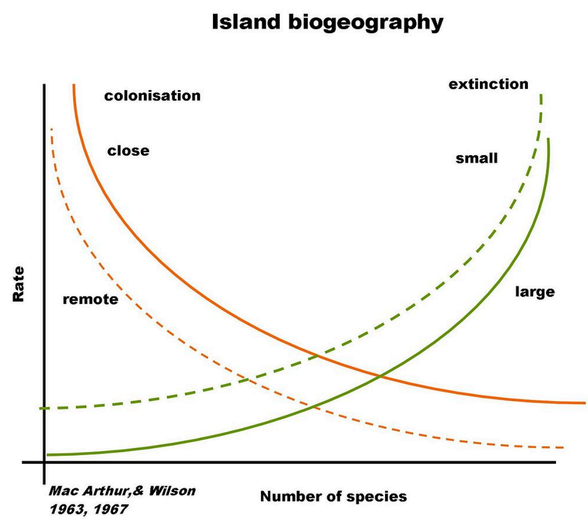
The species-area relationship

Finally, repeated research has shown that the number of species is related to the area studied. This relationship is so strong, that it can be represented mathematically. In general, the number of species (S) in an area (A) can be estimated using an equation, one of the most common of which is

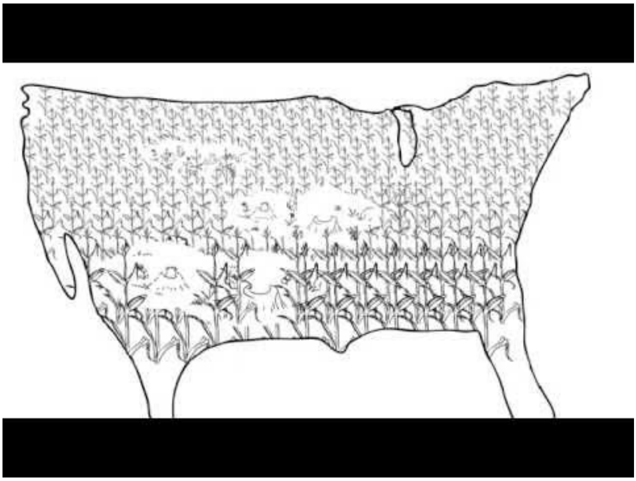
$S = cA^Z$

Z is the slope of a log-log graph of number of species (S), area (A) and c, a constant used depending on the unit of area used (and actually used in other ways too). Given that we just discussed trends in biodiversity with latitude and elevation, the conclusion that Z is not the same in all regions seems obvious. Z also varies depending on the type of species studied, in particular how easily the species can disperse.

One common application of the species-area relationship is in island biogeography. This theory, developed by Robert MacArthur and E. O. Wilson, explains species richness on islands as a combination of the number of species that reach the island and the number of species that go extinct on the island. In general, islands that are close to the mainland will have higher rates of species reaching the island and smaller islands will have higher rates of species extinction for the same number of species on the island. For all islands, the rate of species extinction increases as more species settled the islands. The theory predicts an equilibrium state at which the rate of species immigrating to the island equals the rate of species extinction. This theory has been useful in predicting a sort of steady-state species richness on islands and in more recent years has been expanded to include evolutionary processes at longer time scales. The graph below is a pictorial version of the theory (F.W., CC BY-SA 3.0 DE <https://creativecommons.org/licenses/by-sa/3.0/de/deed.en>, via Wikimedia Commons).



The video below from the California Academy of Sciences gives a great overview of why species are not distribute evenly.



A YouTube element has been excluded from this version of the text. You can view it online here: https://viva.pressbooks.pub/theecosphereandenvironmentalissues/?p=34

Adapted from https://www.oercommons.org/courseware/lesson/15168/overview

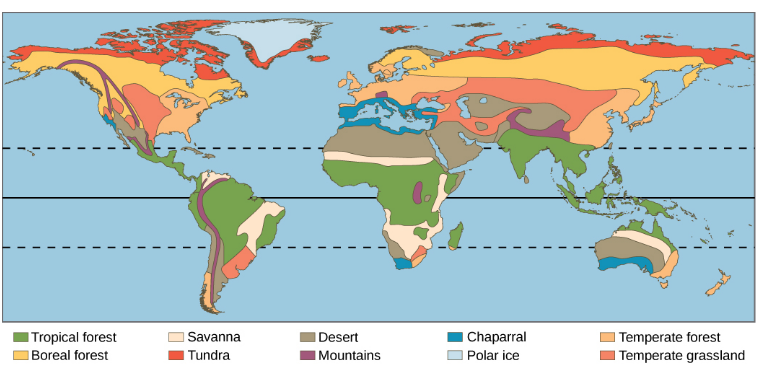


Figure 1. Each of the world's eight major biomes is distinguished by characteristic temperatures and amount of precipitation. Polar ice caps and mountains are also shown.

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

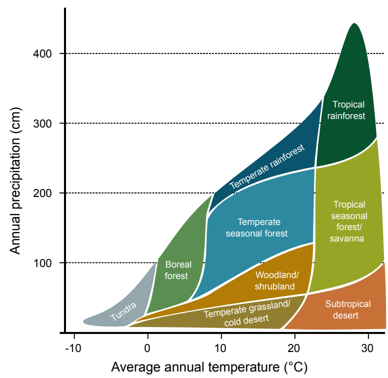


Figure 2. Precipitation and temperature are the two most important climatic variables that determine the type of biome in a particular location. Credit: "Climate influence on terrestrial biome" by Navarras is in the Public Domain, CC0

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

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

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

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

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

Figure 4. A MinuteEarth video about how trees create rainfall, and vice versa.

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

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

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

Figure 6. A MinuteEarth video about the global climate patterns which lead to subtropical deserts.

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

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

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

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

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

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

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

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.

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

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

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

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

Figure 10. Deciduous trees are the dominant plant in the temperate forest. (credit: Oliver Herold)

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

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

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

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

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

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

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

Suggested Supplementary Reading

HHMI. 2018. *Biome Viewer*. [Interactive Website]. Howard Hughes

Medical Institute. <https://www.hhmi.org/biointeractive/biomeviewer>

Attribution

Abiotic Factors Influencing Aquatic Biomes

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

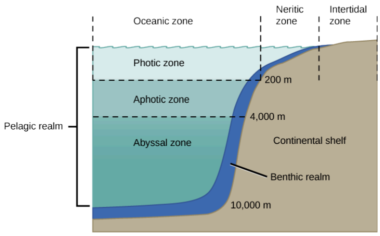


Figure 1. The ocean is divided into different zones based on water depth and distance from the shoreline.

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

Marine Biomes

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

Ocean

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

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

The **neritic zone** (Figure 1) extends from the intertidal zone to depths of about 200 m (or 650 ft) at the edge of the continental shelf. Because light can penetrate this depth, photosynthesis can occur. The water here contains silt and is well-oxygenated, low in pressure, and stable in temperature. Phytoplankton

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

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

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

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

Coral Reefs

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

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

EVOLUTION CONNECTION: Global Decline of Coral Reefs

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

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

Rising levels of atmospheric carbon dioxide further threaten the corals in other ways; as CO_2dissolves in ocean waters, it lowers the pH and increases ocean acidity. As acidity increases, it interferes with the calcification that normally occurs as coral animals build their calcium carbonate homes.

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

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

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

Estuaries: Where the Ocean Meets Fresh Water

Estuaries are biomes 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 (phylum Mollusca), have developed behavioral adaptations that expend a lot of energy to function in this rapidly changing environment. When these animals are exposed to low salinity, they stop feeding, close their shells, and switch from aerobic respiration (in which they use gills) to anaerobic respiration (a process that does not require oxygen). When high tide returns to the estuary, the salinity and oxygen content of the water increases, and these animals open their shells, begin feeding, and return to aerobic respiration.

PART III
EUTROPHICATION

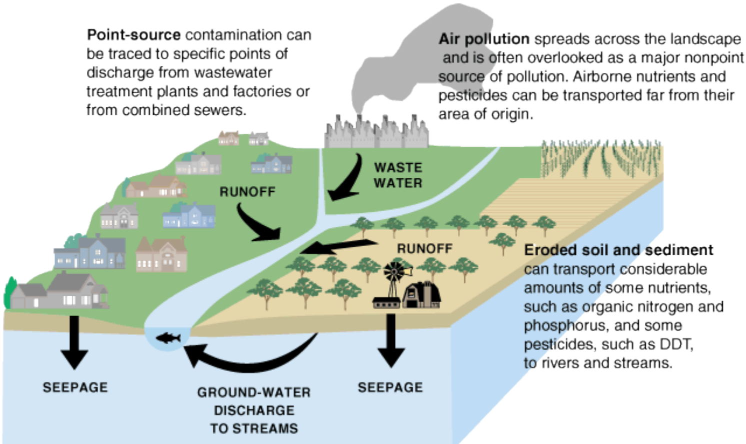
Chemical pollution from agriculture, industry, cities, and mining threatens global water quality. Some chemical pollutants have serious and well-known health effects, whereas many others have poorly known long-term health effects. In the U.S. currently more than 40,000 water bodies fit the definition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

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. In this chapter, we will focus on a specific type of chemical pollution, nutrient pollution, and its impacts.

Water Pollution Overview

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

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

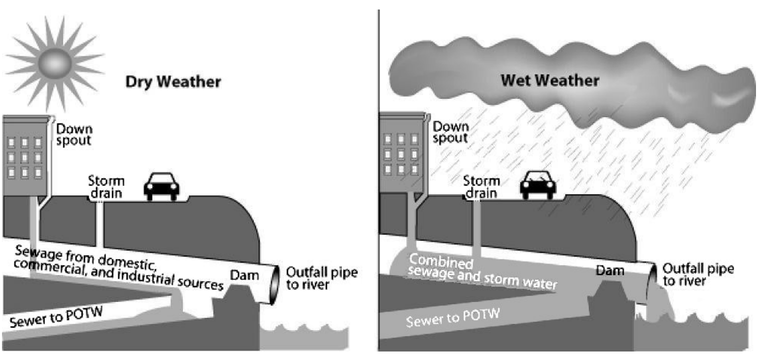


Sources of Water Contamination. Sources of some water pollutants and movement of pollutants into different water reservoirs of the water cycle. Source: U.S. Geological Survey

Pollutants enter water supplies from **point sources**, which are readily identifiable and relatively small locations, or **nonpoint sources**, which are large and more diffuse areas. Point sources of pollution include animal factory farms, such as the one shown to the right, that raise a large number and high density of livestock such as cows, pigs, and

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 chickens. Also, pipes included are pipes from a factories or sewage treatment plants. Combined sewer systems that have a single set of underground pipes to collect both sewage and storm water runoff from streets for wastewater treatment can be major point sources of pollutants. During heavy rain, storm water runoff may exceed sewer capacity, causing it to back up and spilling untreated sewage directly into surface waters, as shown below.

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



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

Types of Water Pollutants

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

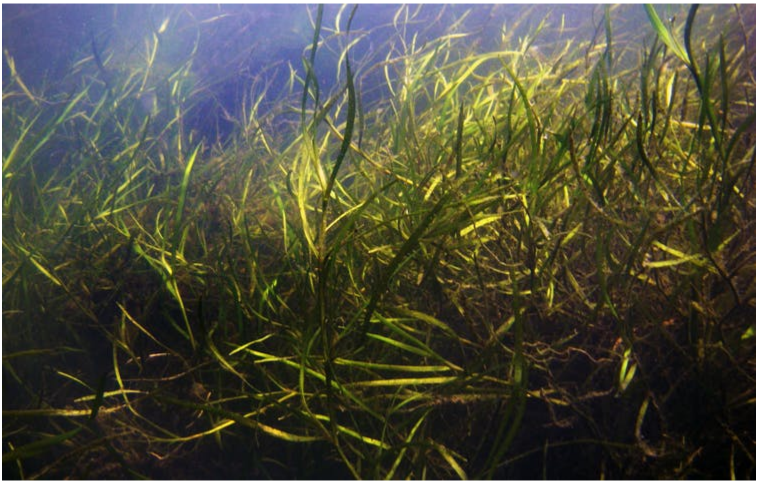
$$\text{organic matter} + O_2 \rightarrow CO_2 + H_2O$$

Too much decaying organic matter in water is a pollutant because it removes oxygen from water, which can kill fish, shellfish, and aquatic insects. The amount of oxygen used by **aerobic** (in the presence of oxygen) bacterial decomposition of organic matter is called **biochemical oxygen demand** (BOD). The major source of dead organic matter in many natural waters is sewage; grass and leaves are smaller sources. An unpolluted water body with respect to BOD is a turbulent river that flows through a natural forest. Turbulence continually brings water in contact with the atmosphere where the O_2 content is restored. The dissolved oxygen content in such a river ranges from 10 to 14 ppm O_2, BOD is low, and clean-water fish such as trout. A polluted water body with respect to oxygen is a stagnant deep lake in an urban setting with a combined sewer system. This system favors a high input of dead organic carbon from sewage overflows and limited chance for water circulation and contact with the atmosphere. In such a lake, the dissolved O_2 content is ≤5 ppm O_2, BOD is high, and low O_2-tolerant fish, such as carp and catfish dominate.

Excessive plant nutrients, particularly nitrogen (N) and phosphorous (P), are pollutants closely related to oxygen-demanding waste. Aquatic plants require about 15 nutrients for growth, most of which are plentiful in water. N and P are called **limiting nutrients**, however, because they usually are present in water at low concentrations and therefore restrict the total amount of plant growth. This explains why N and P are major ingredients in most fertilizer. High concentrations of N and P from human sources (mostly agricultural and urban runoff including fertilizer, sewage, and phosphorus-based detergent) can cause cultural **eutrophication**, which leads to the rapid growth of aquatic producers, particularly algae. Thick mats of floating algae or rooted plants lead to a form of water pollution that damages the ecosystem by clogging fish gills and blocking sunlight. A small percentage of algal species produce toxins that can kill animals, including humans. Exponential growths of these algae are called **harmful algal blooms**. When the prolific algal layer dies, it becomes oxygen-demanding waste, which can create very low O_2 concentrations in the water (< 2 ppm O_2), a condition called **hypoxia.** This results in a **dead zone** because it causes death from asphyxiation to organisms that are unable to leave that environment. An estimated 50% of lakes in North America, Europe, and Asia are negatively impacted by cultural eutrophication. In addition, the size and number of marine hypoxic zones have grown dramatically over the past 50 years including a very large dead zone located offshore Louisiana in the Gulf of Mexico. Cultural eutrophication and hypoxia are difficult to combat, because they are caused primarily by nonpoint source pollution, which is difficult to regulate, and N and P, which are difficult to remove from wastewater.

The Chesapeake Bay has experienced significant cultural eutrophication. Read the article below from The Conversation to learn more about how efforts to reduce eutrophication in the Chesapeake Bay are paying off.

Cutting pollution in the Chesapeake Bay has helped underwater grasses rebound



Healthy aquatic vegetation in the Chesapeake Bay.
Cassie Gurbisz/University of Maryland Center for Environmental Science, CC BY-ND

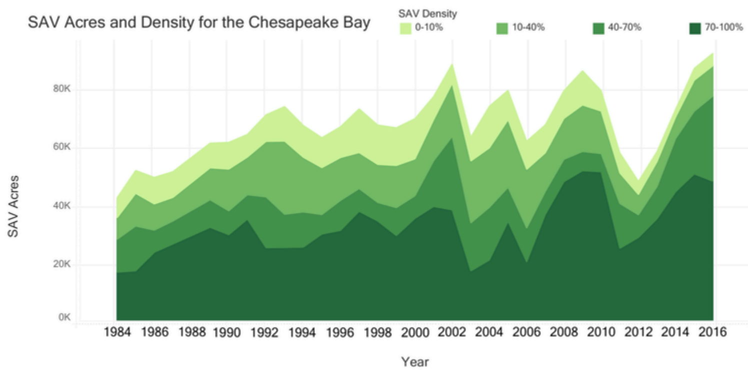
Bill Dennison, *University of Maryland Center for Environmental Science* and Robert J. Orth, *Virginia Institute of Marine Science*

Seagrasses are the "coastal canaries" of oceans and bays. When these underwater flowering plants are sick or dying, it means the ecosystem is in big trouble – typically due to pollution that reduces water quality. But when they are thriving and expanding, it is a sign that the ecosystem is becoming healthier.

We have collaborated on seagrass research for three decades in the Chesapeake Bay and beyond. One of us (Bob "JJ" Orth) has mapped and studied the bay's submerged aquatic vegetation since the 1980s. And the other (Bill Dennison) studies seagrass ecophysiology and has led efforts to make this science understandable and useful.

Seagrasses are critical to a healthy Chesapeake Bay. They provide habitat for fish and shellfish, stabilize sediments and help clarify the water. The bay's grasses declined sharply in the 1970s, as pollution and development degraded its water quality. States around the bay have been working together since 2010 on a sweeping plan to clean it up and restore its ecosystems.

In a new study, we provide conclusive evidence that reducing discharges of nitrogen, phosphorus and other pollutants into the bay has produced the largest resurgence of underwater grasses ever recorded anywhere. This success shows that coastal ecosystems are resilient and that concerted efforts to reduce nutrient pollution can result in substantial improvements.



Trends in acreage and density of submerged aquatic vegetation in the Chesapeake Bay.

Cutting nutrient pollution boosts seagrasses

Ten years ago we led an effort through the National Center for Ecological Analysis and Synthesis to understand the global trajectories of seagrasses. What we found was that seagrasses were being lost at an alarming rate, equivalent to a soccer field of seagrass every 30 minutes since 1980.

So when we began to observe net increases over the past few years in the abundance of multiple types of seagrasses (collectively known as submerged aquatic vegetation) in our beloved Chesapeake Bay, we knew this event was globally unique.

To discern what was happening, we partnered with the Chesapeake Bay Program to initiate what is called a synthesis effort. Synthesis science brings together diverse teams of experts from different fields to pull new insights out of existing data.

Pollution sources throughout the Bay's watershed affect its water quality.
USGS

We had access to 30 years of annual surveys of underwater grasses that JJ Orth personally oversees, plus a 30-year water quality data set collected by the Chesapeake Bay Program. Scientists from the Virginia Institute of Marine Science, University of Maryland Center for Environmental Science, Bigelow Laboratory for Ocean Sciences, the U.S. Geological Survey, the National Socio-Environmental Synthesis Center, St. Mary's College of Maryland, the Smithsonian Environmental Research Center, the Maryland Department of Natural Resources, Texas A&M University-Corpus Christi and the U.S. Environmental Protection Agency provided analytical firepower to help assess this complex information.

We started by identifying ways in which activities on land could affect trends in water quality and underwater grass abundance. Then we tested our hypothesized linkages using structural equation models that analyzed data in two different ways.

One approach focused on the cascade of nitrogen and phosphorus moving from sources on land, such as wastewater discharge and stormwater runoff, into waterways. The other showed what happened to underwater grasses once these nutrients entered in the water. Nutrients overfertilize the bay, creating huge blooms of algae that die and deplete oxygen from the water. This produces "dead zones" that cannot support fish or plant life.

Historic photos show water quality declining and underwater grasses disappearing off Solomons, Maryland.

In our analysis, we found conclusive evidence that reductions of excess nitrogen and phosphorus caused the underwater grass recovery in the Chesapeake Bay. Since 1984, the quantity of nitrogen entering the bay has decreased by 23 percent and phosphorus has fallen by 8 percent, thanks to a “pollution diet” that the EPA established in 2010. The plan, formally called a Total Maximum Daily Load (TMDL), requires states in the bay’s 64,000-square mile watershed to reduce specific pollutants entering the bay to target levels on a fixed schedule.

As a result, underwater grasses have increased by over 300 percent and have reappeared in some locations around the bay where they had not been observed for decades.

A healthier Chesapeake Bay

For the past 12 years, we have been using underwater grasses and other water quality data to produce an annual Chesapeake Bay report card. Our 2017 report card describes progress across the board, with 7 out of 15 reporting regions around the bay showing significant improvement and the rest holding steady.

We attribute these improvements to the TMDL plan. In particular, upgrades at area wastewater treatment facilities have reduced nitrogen and phosphorus inputs into the bay. Catalytic converters on automobiles and smokestack scrubbers in power plants have reduced atmospheric nitrogen emissions and subsequent deposition that finds its way into bay waters. It appears that these management actions are beginning to pay off, although there is more to do – especially reducing nutrient pollution from agriculture.

https://youtube.com/watch?v=z3-XhBU08xM%3Fwmode%3Dtransparent%26start%3D0

Seagrasses in the Chesapeake Bay’s Susquehanna Flats are rebounding.

Progress at risk

The Chesapeake Bay Program is a partnership between six states (New York, Pennsylvania, Maryland, Delaware, West Virginia, Virginia), the District of Columbia and the federal government, represented by the EPA. It heavily leverages federal funding by engaging community groups, local municipalities and nongovernmental organizations to carry out actions that help reduce pollution entering the bay. Examples include re-engineering urban surfaces to reduce stormwater runoff and subsidizing farmers to grow winter cover crops that help retain nutrients on fields.

When EPA Administrator Scott Pruitt was Oklahoma's attorney general, he joined other states in a lawsuit to block the Chesapeake Bay cleanup, calling it a federal overreach. Now, however, Pruitt has pledged to support the program, which was upheld by a federal court in 2013 and sustained on appeal in 2015.

But President Trump's 2017 budget called for eliminating the Chesapeake Bay Program completely. Congress enacted only small cuts, but Trump's 2018 budget request cuts the program's funding by 90 percent – ironically, just when we are finally starting to reverse degradation from past decades.

The Chesapeake Bay is arguably the best-studied estuary on the planet, and the fact that our study connects management actions to a huge resurgence of underwater grasses is a tribute to this rich history. Ongoing efforts to restore the bay have produced lessons about how pollution abatement can lead to ecosystem recovery.

These insights can and should be applied to other water bodies affected by nutrient pollution. We hope the story of the Chesapeake Bay's recovery inspires similar actions in many other places.

Bill Dennison, Professor of Marine Science and Vice President for Science Applications, *University of Maryland Center for Environmental Science* and Robert J. Orth, Professor of Marine Science, *Virginia Institute of Marine Science*

Attribution

5. Energy in ecosystems

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

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

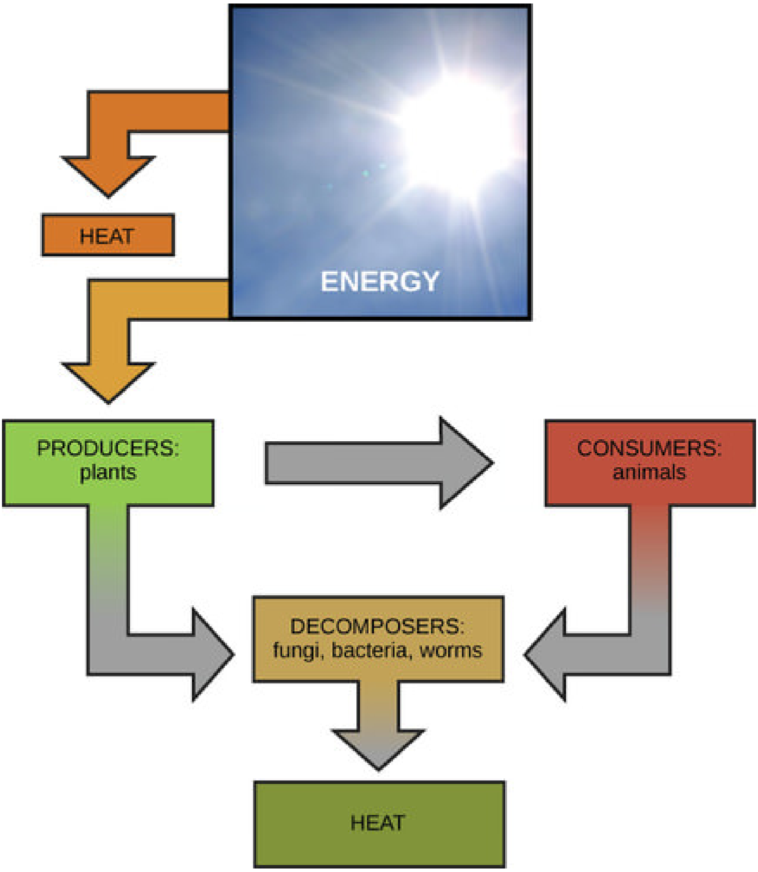


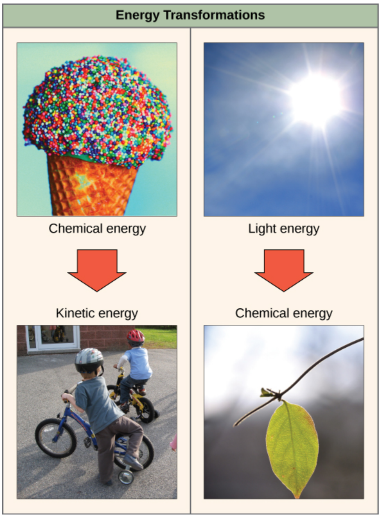
Figure 1. Ultimately, most life forms get their energy from the sun. Plants use photosynthesis to capture sunlight, and herbivores eat the plants to obtain energy. Carnivores eat the herbivores, and eventual decomposition of plant and animal material contributes to the nutrient pool.

Energy

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

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

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



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

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

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. When we say that energy is lost, we are not saying it disappears (this would violate the first law of thermodynamics). We are saying that is becomes unusable, usually because it become heat. For example, if I am riding my bike, I am transforming chemical energy from the food I ate into kinetic energy (energy of motion). This kinetic energy is usable and moves me from place to place or could move another object, for example, if I ran into a small trash can. If instead of running into the trash can, I braked hard and came to a quick stop, my kinetic energy would be transformed to heat. I could feel it if I touched my tires.

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

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

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

Solar Dependence and Food Production

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

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

Chemoautotrophs are organisms that use inorganic molecules as an energy source. Chemoautotrophs are much less abundant than photoautotrophs and are often found in extreme environments such as near deep-seafloor hydrothermal vents.

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

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

Summary of Photosynthesis

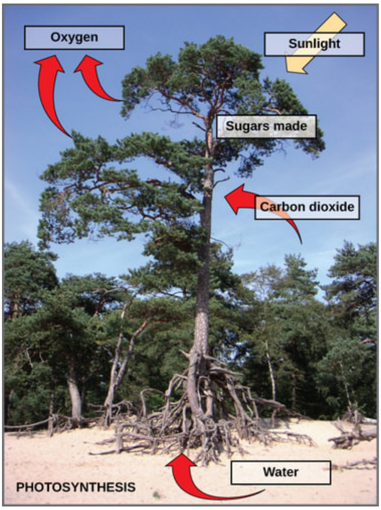


Figure 3. Photosynthesis uses solar energy, carbon dioxide, and water to release oxygen and to produce energy-storing sugar molecules.

Photosynthesis requires sunlight, carbon dioxide, and water as starting reactants (Figure 3). After the process is complete, photosynthesis releases oxygen and produces carbohydrate molecules, most commonly glucose. These sugar molecules contain the energy that living things need to survive. The complex reactions of photosynthesis can be summarized by the chemical equation shown below. Although the equation looks simple, the many steps that take place during photosynthesis are actually quite complex. In plants, photosynthesis takes place primarily in the chloroplasts of leaves. Chloroplasts have a double (inner and outer) membrane. Within the chloroplast is a third membrane that forms stacked, disc-shaped structures called thylakoids. Embedded in the thylakoid membrane are molecules of **chlorophyll**, a pigment (a molecule that absorbs light) through which the entire process of photosynthesis begins.

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

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

The Two Parts of Photosynthesis

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

The Global Significance of Photosynthesis

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

1. It creates O_2, which is important for two reasons. The molecular oxygen in Earth's atmosphere was created by photosynthetic organisms; without photosynthesis there would be no O_2 to support cellular respiration needed by complex, multicellular life. Photosynthetic bacteria were likely the first organisms to perform photosynthesis, dating back 2-3

billion years ago. Thanks to their activity, and a diversity of present-day photosynthesizing organisms, Earth's atmosphere is currently about 21% O_2. Also, this O_2 is vital for the creation of the ozone layer, which protects life from harmful ultraviolet radiation emitted by the sun. Ozone (O_3) is created from the breakdown and reassembly of O_2.

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

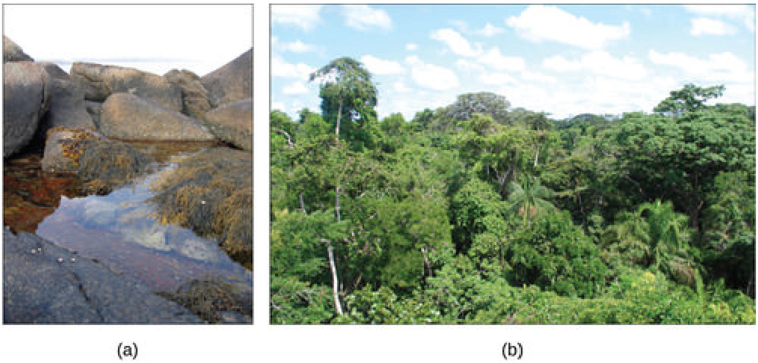


Figure 1. A (a) tidal pool ecosystem in Matinicus Island, Maine, is a small ecosystem, while the (b) Amazon rainforest in Brazil is a large ecosystem. (credit a: modification of work by Jim Kuhn; credit b: modification of work by Ivan Mlinaric)

Food Chains and Food Webs

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

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

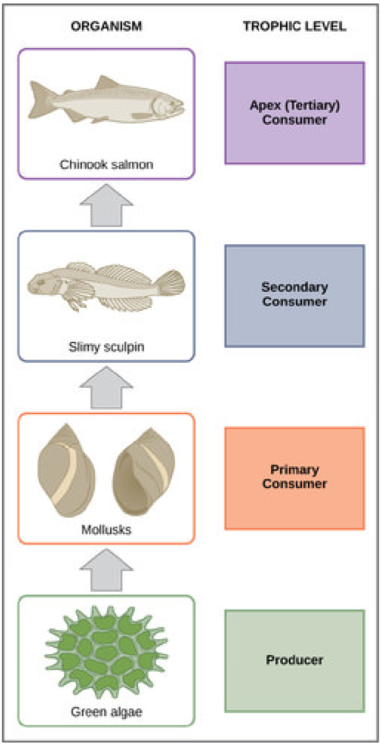
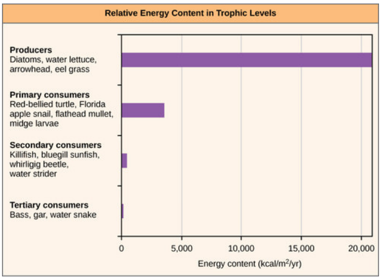


Figure 3. These are the trophic levels of a food chain in Lake Ontario at the United States–Canada border. Energy and nutrients flow from photosynthetic green algae at the base to the top of the food chain: the Chinook salmon. (credit: modification of work by National Oceanic and Atmospheric Administration/NOAA)

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

One major factor that limits the number of steps in a food chain is energy. Energy is lost at each trophic level and between trophic levels as heat and in the transfer to decomposers. The loss of energy between trophic levels is illustrated by the pioneering studies of Howard T. Odum in the Silver Springs, Florida, ecosystem in the 1940s. Some of the data from this study is shown below. The primary producers generated 20,819 kcal/m^2/yr (kilocalories per square meter per year), the primary consumers generated 3368 kcal/m^2/yr, the secondary consumers generated 383 kcal/m^2/yr, and the tertiary consumers only generated 21 kcal/m^2/yr. Thus, there is little energy remaining for another level of consumers in this ecosysem.



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

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

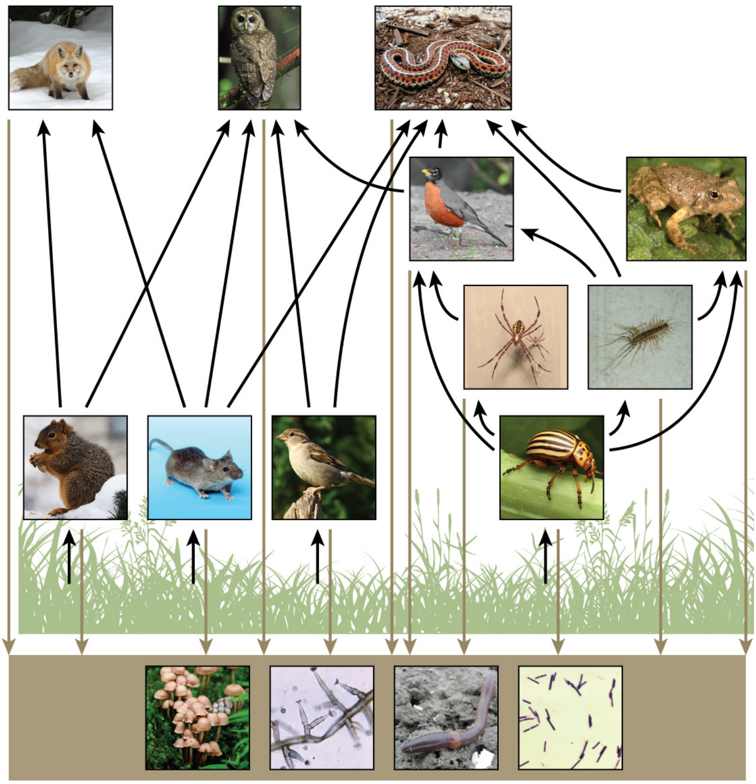


Figure 5. This food web shows the interactions between organisms across trophic levels. Arrows point from an organism that is consumed to the organism that consumes it. All the producers and consumers eventually become nourishment for the decomposers (fungi, mold, earthworms, and bacteria in the soil).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

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

Productivity within Trophic Levels

Productivity within an ecosystem can be defined as the percentage of energy entering the ecosystem incorporated into biomass in a particular trophic level. **Biomass** is the total mass, in a unit area at the time of measurement, of living or previously living organisms within a trophic level. Ecosystems have characteristic amounts of biomass at each trophic level. For example, in the English Channel ecosystem the primary producers account for a biomass of 4 g/m^2 (grams per meter squared), while the primary consumers exhibit a biomass of 21 g/m^2.

Because all organisms need to use some of this energy for their own functions (like respiration and resulting metabolic heat loss) scientists often refer to the net primary productivity of an ecosystem. Net primary productivity is the energy that remains in the primary producers after accounting for the organisms' respiration and heat loss. The net productivity is then available to the primary consumers at the next trophic level. In our Silver Spring example, 13,187 of the 20,810 $kcal/m^2/yr$ were used for respiration or were lost as heat, leaving 7,632 $kcal/m^2/yr$ of energy for use by the primary consumers.

Primary productivity provides energy to the ecosystem

Gross primary productivity is the rate at which solar or chemical energy is captured and converted into chemical bonds by producers in an area. Producers use energy for their own respiration, growth, and reproduction.When energy that is assimilated by producers and converted into producer biomass in an area is called **net primary productivity** (NPP). NPP includes all energy that is not respired.

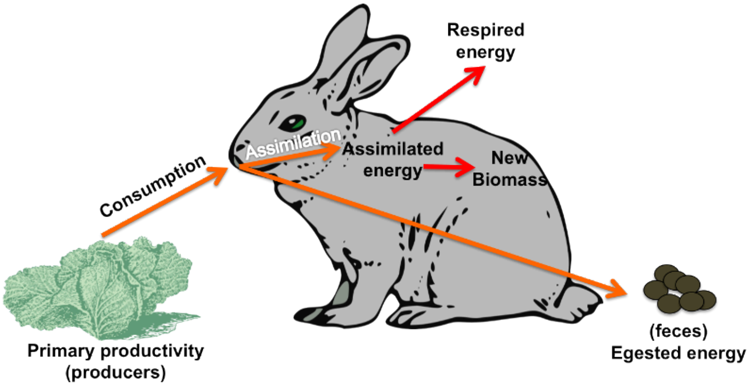
NPP = GPP – Respiration (Both GPP and NPP are expressed in units of Joules (J) / m^2 / year.)

However, photosynthesis is not a very efficient process. Only 1% of solar energy is captured and used by photosynthesis, which is gross primary productivity

Secondary production

Herbivores consume only a fraction of the total producer biomass available. They can only digest a portion of the energy they consume. **Secondary production** is the amount of assimilated energy converted into new biomass (growth and reproduction) by herbivores.

The image below shows that a rabbit consumes on the cabbage (primary production provied by the producers), a process we called **consumption**. A small protion of consumed energy that is excreted or regurgitated is the **egested energy**. The portion of consumed energy that the rabbit digests and absorbs is called **assimilated energy** (assimilation; analogous to GPP for producers). The rabbit uses a portion of assimilated energy for respiration, which is called **respirated energy**. The remaining assimilated energy can be used for *growth and reproduction*, which is called **net secondary productivity**.



This diagram shows a rabbit (primary consumer) consumes the cabbage (producer). The consumed energy is either excreted as waste (egested energy; non-assimilated energy) or converted into assimilated energy (including respired energy and biomass-secondary productivity) (Diagram created by Dr. Ching-Yu Huang, Biology instructor, Virginia Commonwealth University, VA by adapting images: Rabbit, Openclipart. CC0 Public Domain and Cabbage, Openclipart. CC0 Public Domain)

The efficiency of energy transfers within organisms

1.**Consumption efficiency** is the percentage of energy (J for joules) or biomass in a trophic level that is consumed by the next higher trophic level.

$$\text{Consumption efficiency} = \frac{\text{Consumed energy (J)}}{\text{Net production energy of the next lower trophic level (J)}}$$

Primary productivity is the energy content in producers that is available to the organisms of the next trophic level (which is primary consumers; herbivores). **Secondary productivity** is the availble evergy content in the primary consumer to the next tropic level (i.e.

secondary consumer, carnivores). You will use primary productivity as "Net production energy of the next lower trophic level" in the equation above, when you are calculating the consumption efficiency for primary consumer. And you will use secondary productivity as "Net production energy of the next lower trophic level" in the equation above, when you are calculating the consumption efficiency for seconary consumer.

2. The percentage of consumed energy by an organims that is assimilated in the body of the consumer (i.e., material that is not egested) is called **assimilation efficiency**. It is calculated based on the amount of assimialted energy divided by the consumed energy.

$$\text{Assimilation efficiency} = \frac{\text{Assimilated energy (J)}}{\text{Consumed energy (J)}}$$

Assimilation efficiency varies among trophic levels. Primary consumers (i.e. herbivores) tend to have lower efficiencies than secondary consumers because animal tissues are more digestible than plant tissues (contain many undigestible materials, such as fibers and lignin).

3. **Net production efficiency** is the percentage of assimilated energy that is used for *growth* and *reproduction*. You may also consider that net production efficiency is the percentage of assimilated energy that remains after an organism' respiration.

$$\text{Net production efficiency} = \frac{\text{Net production energy (J)}}{\text{Assimilated energy (J)}}$$

Net production efficiency (NPE) allows ecologists to quantify how efficiently organisms of a particular trophic level incorporate the energy they receive into biomass. Thus, net production efficiency measures how efficiently each trophic level uses and incorporates the energy from its food into biomass to fuel the next trophic level.

For active homeothermic animals, they spend significant amount of energy to maintain body temperature, move, circulate blood, and osmoregulate, so their net production efficiency can be as low as 1%. In general, cold-blooded animals (ectotherms), such as invertebrates, fish, amphibians, and reptiles, use less of the energy they obtain for respiration and heat than warm-blooded animals (endotherms), such as birds and mammals. The extra heat generated in endotherms, although an advantage in terms of the activity of these organisms in colder environments, is a major disadvantage in terms of net production efficiency. Therefore, many endotherms have to eat more often than ectotherms to get the energy they need for survival. In general, NPE for ectotherms is an order of magnitude (10x) higher than for endotherms. For example, the NPE for a caterpillar eating leaves has been measured at 18 percent, whereas the NPE for a squirrel eating acorns may be as low as 1.6 percent.

The inefficiency of energy use by warm-blooded animals 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 the NPE is low, 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. Much of this difference is due to the low NPE of cattle. 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.

Ecological Efficiency: The Transfer of Energy between Trophic Levels

As illustrated in Silver Springs ecosystem, large amounts of energy are lost from the ecosystem from one trophic level to the next level as energy flows from the primary producers through the various trophic levels of consumers and decomposers. The main reason for this loss is the second law of thermodynamics, which states that whenever energy is converted from one form to another, there is a tendency toward disorder (entropy) in the system. In biologic systems, this means a great deal of energy is lost as **metabolic heat** when the organisms from one trophic level consume the next level. In the Silver Springs ecosystem example, we see that the primary consumers produced 1103 kcal/m^2/yr from the 7618 kcal/m^2/yr of energy available to them from the primary producers. The measurement of energy transfer efficiency between two successive trophic levels is termed the **ecological efficiency** and is defined by the formula:

Ecological efficiency (also called food chain efficiency) is the percentage of net production from one trophic level compared to the next lower trophic level.

$$\text{Ecological efficiency} = \frac{\text{Net production energy of a trophic level (J)}}{\text{Net production energy of the next lower trophic level (J)}}$$

Ecological efficiency incorporates consumption, assimilation, and net production efficiency. Because energy is lost at each of these processes, ecological efficiency is usually low, ranging from 5% to 20%. However, 10% is used as a rule of thumb.

For example, in Silver Springs, the ecological efficiency between the first two trophic levels was approximately 14.8 percent. The low efficiency of energy transfer between trophic levels is usually the major factor that limits the length of food chains observed in a food web. The fact is, after four to six energy transfers, there is not enough energy left to support another trophic level. In the Lake Ontario example, only three energy transfers occurred between the primary producer, (green algae), and the apex consumer (Chinook salmon).

Ecologists have many different methods of measuring energy transfers within ecosystems. Some transfers are easier or more difficult to measure depending on the complexity of the ecosystem and how much access scientists have to observe the ecosystem. In other words, some ecosystems are more difficult to study than others, and sometimes the quantification of energy transfers has to be estimated.

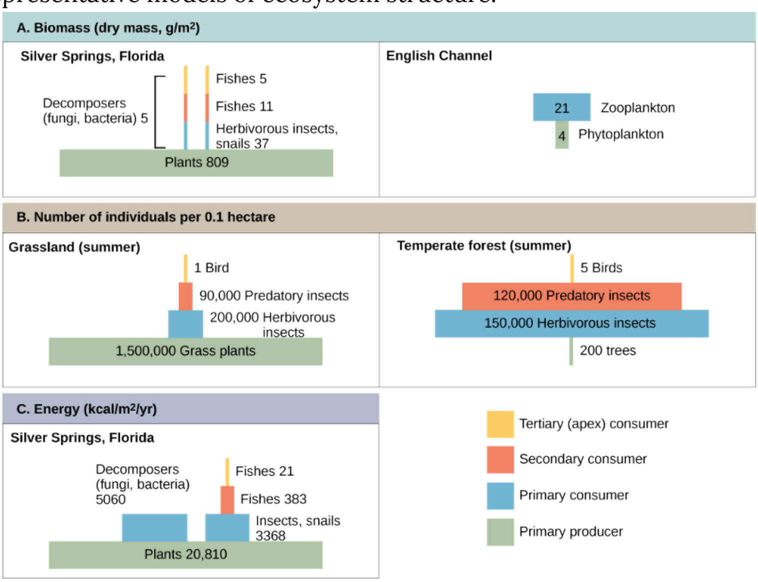
Modeling Energy Flow: Ecological Pyramids

The structure of ecosystems can be visualized with **ecological pyramids**, which were first described by the pioneering studies of Charles Elton in the 1920s. Ecological pyramids show the relative amounts of various parameters (such as number of organisms, energy, and biomass) across trophic levels.

Pyramids of numbers can be either upright or inverted, depending on the ecosystem. As shown at the bottom of this section, a typical grassland during the summer has a base of many plants and the numbers of organisms decrease at each trophic level. However, during the summer in a temperate forest, the base of the pyramid consists of few trees compared with the number of primary consumers, mostly insects. Because trees are large, they have great photosynthetic capability, and dominate other plants in this ecosystem to obtain sunlight. Even in smaller numbers, primary producers in forests are still capable of supporting other trophic levels.

Another way to visualize ecosystem structure is with pyramids of biomass. This pyramid measures the amount of energy converted into living tissue at the different trophic levels. Using the Silver Springs ecosystem example, this data exhibits an upright biomass pyramid, whereas the pyramid from the English Channel example is inverted. The plants (primary producers) of the Silver Springs ecosystem make up a large percentage of the biomass found there. However, the phytoplankton in the English Channel example make up less biomass than the primary consumers, the zooplankton. These two pyramids are included in the figure at the end of this section. As with inverted pyramids of numbers, this inverted pyramid is not due to a lack of productivity from the primary producers, but results from the high turnover rate of the phytoplankton. The phytoplankton are consumed rapidly by the primary consumers, thus, minimizing their biomass at any particular point in time. However, phytoplankton reproduce quickly, thus they are able to support the rest of the ecosystem.

Pyramid ecosystem modeling can also be used to show energy flow through the trophic levels. Notice that these numbers are the same as those used in the energy flow compartment diagrams. Pyramids of energy are always upright, and an ecosystem without sufficient primary productivity cannot be supported. All types of ecological pyramids are useful for characterizing ecosystem structure. However, in the study of energy flow through the ecosystem, pyramids of energy are the most consistent and representative models of ecosystem structure.



Ecological pyramids depict the (a) biomass, (b) number of organisms, and (c) energy in each trophic level in aquatic (Silver Spring and English Channel ecosystems) and terrestrial ecosystems (grassland and temperate forest).

Consequences of Food Webs: Biological Magnification

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

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

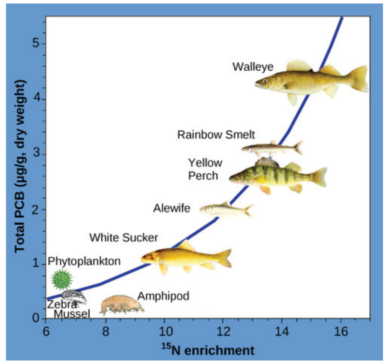


Figure 7. This chart shows the PCB concentrations found at the various trophic levels in the Saginaw Bay ecosystem of Lake Huron. Notice that the fish in the higher trophic levels accumulate more PCBs than those in lower trophic levels. (credit: Patricia Van Hoof, NOAA)

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

Consequences of Food Webs: Trophic Cascades

The interdependence of organisms in an ecosystem through the food webs means that changes to one type of organism can affect other organisms. For example, in the example of the Silver Springs ecosystem, if one of the primary producers, such as the eelgrass, died off in the area, the primary consumers would eat more of the other primary producers, decrease in abundance due to lack of food or some combination of the two. What is less obvious is that a change in one trophic level (such as a secondary consumer) may have indirect effects on a non-adjacent trophic level (such as primary producers). This is called a trophic cascade. One classic example of the importance of trophic cascades is seen in the ecological role of wolves in Yellowstone National Park. Watch the video below to learn more.

A YouTube element has been excluded from this version of the text. You can view it online here: https://viva.pressbooks.pub/theecosphereandenvironmentalissues/?p=133

The impact of the wolves in Yellowstone Park on lower trophic levels is an example of top-down control, the higher trophic level has impacts on multiple lower trophic levels. This type of control was originally thought to be fairly rare, but may be more common than we think. Some systems exhibit bottom-up control in which the primary producers control the abundance at the upper trophic levels. In these instances, the growth of the primary producers is typically limited by some resource, such as nutrient or water, and increasing the amount of that resource would increase the biomass of the primary producer and the upper trophic levels.

Suggested Supplementary Reading

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

Attribution

6. Biogeochemical cycles

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

Mineral nutrients are cycled, either rapidly or slowly, through the entire biosphere, from one living organism to another, and between the biotic and abiotic world. Unfortunately, recent human activities have significantly altered the biogeochemical cycles. In this chapter, we will learn about **carbon**, **nitrogen**, and **phosphorus** cycles.

Introduction to Carbon Cycle

Processses that regulate the carbon cycle

The importance of the carbon cycle

After oxygen (O), **Carbon (C)** is the second most abundant element in living organisms. Carbon is present in all organic molecules, and its role in the structure of macromolecules is of primary importance to living organisms. Carbon compounds contain high energy (such as carbohydrates). Therefore, the movement of carbon (C) in ecosystems largely follows the same paths as the movement of energy.

Fossilized organisms (also called **fossil fuel**), mainly plants, have been utilized as a source of fuel by humans. Since the 1800s, the number of countries using massive amounts of fossil fuels has increased and the global demand for the Earth's limited fossil fuel supplies has risen since the Industrial Revolution. As we learned in Part 1, the amount of carbon dioxide (CO_2) in our atmosphere has increased in the recent decades. Such increase in carbon dioxide has been associated with climate change and other disturbances of the Earth's ecosystems, which has become a major environmental concern worldwide. The concept of "**carbon footprint**" is based on how much carbon dioxide (and other C-compounds, e.g. methane-CH_4) is produced via burning fossil fuel by a person, an area or a country. Carbon dioxide (and other greenshouse gases) is emitted via your daily activities, such as using eletricity, driving car and disposing waste. By calculating carbon footprint, we can evalute and compare our impacts (therefore called "footprint") to our environment.

Watch the video Episode 1: Global Warming. It's All About Carbon by Robert Krulwich and Odd Todd from National Public Radio (Standard YouTube License).

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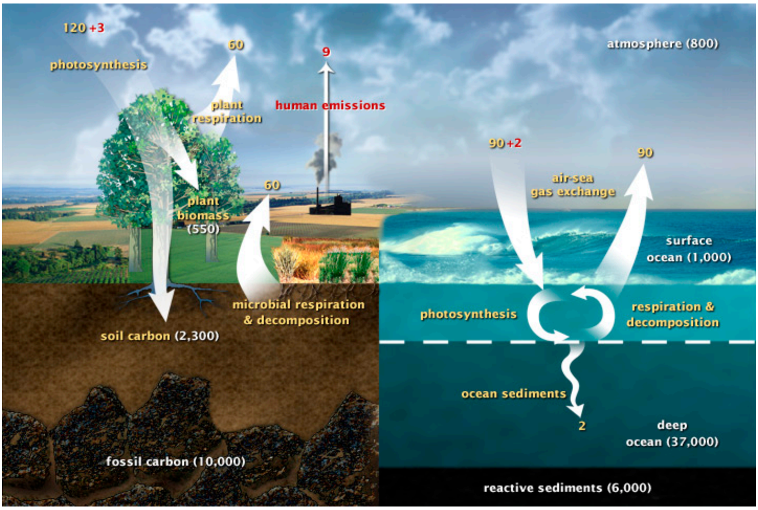
Biotic and abiotic reservoirs of carbon

The movement of carbon through land, water, and air is complex, and in many cases, it occurs more slowly geologically than the movement between living organisms. Carbon is stored for long periods in what are known as **carbon reservoirs**, which include the atmosphere, bodies of liquid water (mostly oceans), ocean sediments, soils, land sediments (including fossil fuels), and the Earth's interior. The carbon cycle is most easily studied as two interconnected sub-cycles: one dealing with rapid carbon exchange among living organisms and the other dealing with the long-term cycling of carbon through geologic processes. The fast carbon cycle and reservoirs of the slow carbon cycle are shown in the diagram below.



This diagram of the fast carbon cycle shows the movement of carbon between land, atmosphere (left), and oceans (right). Yellow numbers are natural fluxes, and red are human contributions in gigatons of carbon per year. White numbers indicate stored carbon. Because the fluxes in the slow carbon cycle are so slow, they are not shown on this diagram. [Carbon cycle diagram. National Aeronautics and Space Administration (NASA) Earth Observatory. Diagram adapted from the U.S. Department of Education (DOE) Biological and Environmental Research Information System. Public Domain](Credit: Holli Riebeek)

As shown in the figure, the **atmosphere** is a major reservoir of carbon in the form of **carbon dioxide** (CO_2) and is essential to the process of photosynthesis. The level of carbon dioxide in the atmosphere is 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 location, and each one affects the other reciprocally.

Seven processes that drive the carbon cycle

1. Photosynthesis

When performing photosynthesis, most terrestrial autotrophs obtain their carbon dioxide directly from the atmosphere, while marine autotrophs acquire it in the dissolved form (carbonic acid, $H_2CO_3^{2-}$). As carbon dioxide (and water) is acquired for photosynthesis, the products of the process are oxygen (O_2) and sugar ($C_6H_{12}O_6$) for energy. The photosynthetic organisms are responsible for depositing the approximately 21 percent oxygen content of the atmosphere that we observe today. The figure below shows a simple schematic of the materials moving into and out of a leaf during photosynthesis along with the equation for photosynthesis on the right (Image credit: Vojtech.dostal, Wikimedia commons

$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} \xrightarrow{\text{Light}} \underset{\text{Sugar}}{6C_6H_{12}O} + \underset{\text{Oxygen}}{6O_2}$$

2. Respiration (by all living organisms)

During **cellular respiration**, living organisms break down organic carbon compounds to produce energy (such as ATP) and CO_2 and water are released as by-products. The most efficient type of respiration, aerobic respiration, requires oxygen obtained from the atmosphere or dissolved in water. Thus, there is a constant exchange of oxygen and carbon dioxide between autotrophs (which need carbon) and heterotrophs (which need oxygen). Gas exchange through the atmosphere and water is one way that the carbon cycle connects all living organisms on Earth.

3. Consumption

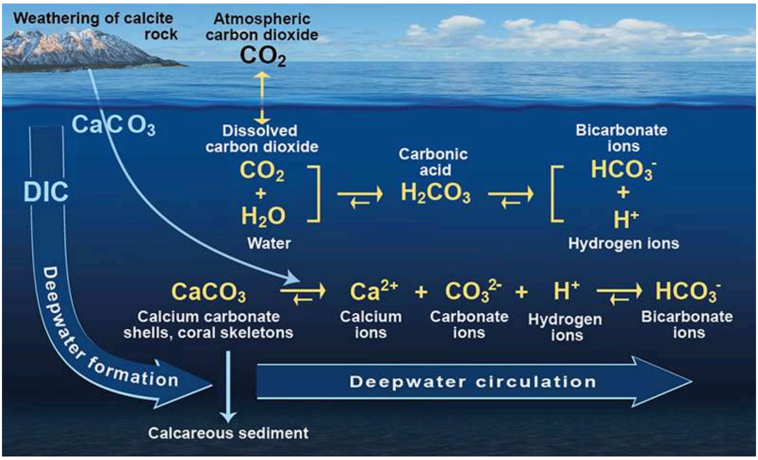
Living organisms are connected in many ways. A good example of this connection is the exchange of carbon between autotrophs and heterotrophs and between different heterotrophs by way of organic carbon compounds. Most autotrophs use carbon dioxide to build multi-carbon, high energy organic compounds, such as glucose. The energy harnessed from the sun is used by producers to form the covalent bonds that link carbon atoms together. The bonds in long carbon chains contain chemical energy. When the chains break apart, the stored energy is released for later use in the process of cellular respiration or tissue production.

Autotrophs and heterotrophs (especially the primary consumers, largely herbivores are partners in biological carbon exchange. Heterotrophs acquire high-energy carbon compounds from the autotrophs by consuming them, and breaking them down through respiration to obtain cellular energy, such as ATP (**Figure 16.5**).

Herbivores, like this mule deer (left) and monarch caterpillar (right), eat primarily plant material. The process of consumption by herbivores transfers the chemcal energy stored in producers (plants) into the chemical energy (as organic carbon compounds) in the heterotrophs. The energy is used later for cellular respiration and secondary production (credit left: modification of work by Bill Ebbesen; credit right: modification of work by Doug Bowman)

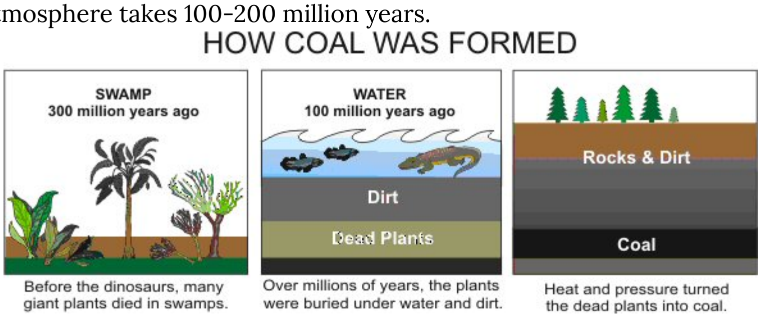
4. Gas exchange between oceans and atmosphere

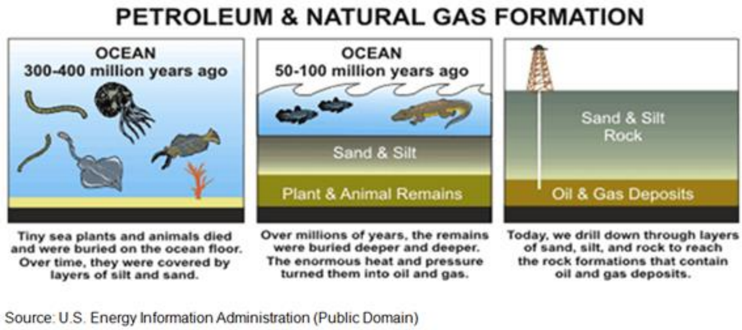
As stated previously, gas exchange of carbon between the atmosphere and water reservoirs can affect carbon fluxes and carbon storage at each location. For example, an increased level of carbon dioxide in the atmosphere can greatly change the reservoir of carbon in the oceans. Atmospheric carbon dioxide (CO_2) dissolves in water and combines with water molecules to form carbonic acid ($H_2CO_3^{2-}$), and then it ionizes to carbonate (CO_3^{2-}) and bicarbonate ions (HCO_3^-) as shown in the figure below (Solubility carbon pump. Credit: NOC/V.Byfield. The National Archives UK. Open Government License (OGL)]). Naturally, such atmosphere-ocean carbon exchange occurs in both directions at a similar magnitude. There is often little net transfer over time. Some of the carbon dioxide that is diffused in the oceans can be used either by plants and phytoplankton for photosynthesis, or converted into carbonate and bicarbonate ions. Such surface ocean-atmosphere CO_2 gas exchange occurs at a relatively short time scale. Most of the anthropogenic carbon released in the past decades are taken up by the ocean and stored in the deep ocean as sediments for a long time.



5. Sedimentation / Burial

Sedimentation and burial are largely processes in the slow carbon cycle. Carbon dioxide in the atmosphere is dissolved in rainfall to form a weak acidic solution, which dissolves minute amounts of rock when it hits the ground. This process, called chemical weathering releases more carbon and ions like calcium and sodium which are then carried to the ocean. Once in the ocean, carbon, oxygen and calcium bond to form calcium carbonate ($CaCO_3$) in animal shells and coral skeletons. When these animals die, the shells and skeletons sink to the bottom of the ocean and can be buried. Over time, as more and more layers of shells and skeletons build up, these particles become cemented together to become rocks like limestone. About 80% of the carbon stored in rocks in stored this way. The other 20% comes from organic matter, like leaves, getting buried in mud and other organic matter faster than it can decompose. With time and pressure, this organic matter and the surrounding mud forms sedimentary rocks like shale and some is converted to fossil fuels (as shown below). The deposition of the carbon material, whether it is shells, skeletons of organic matter, is called **sedimentation**. The deposition of additional material on top is called burial. When carbon is burried as organic matter before it is fully decomposed, some of it The transformation of these materials into rock is called lithification. Carbon stored in the sediment can be returned to the atmosphere through volcanoes to begin the carbon cycle again. Moving from atmosphere to ocean to rock and back to atmosphere takes 100-200 million years.





The diagrams above describe how coal (top), and petroleum and natural gas (bottom) are formed during the burial and geological processes. (Formation of Fossil Fuels. Originally uploaded in EarthLabs: Climate and the Carbon Cycle . U.S. Department of Energy National Science Foundation (NSF) Public Domain)

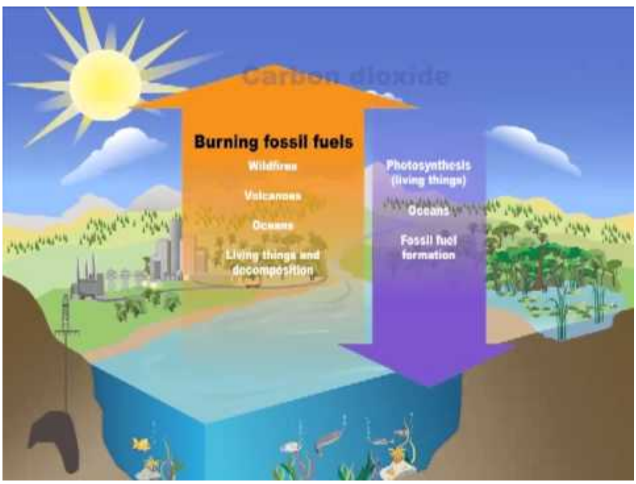
6. Decomposition

The process where dead organic matter (dead animals and dead plants) and organic substances are broken down into simple inorganic carbon forms is called **decomposition**. In this process, carbon in the organic matter is converted into inorganic carbon dioxide gas, which is released back to atmosphere. Decomposition relies on cellular respiration of bacteria and fungi (decomposers); therefore it is related to rates of microbial respiration.

7. Combustion

The **combustion** of organic matter and/or fossil fuels releases CO_2 back into the atmosphere. Some combustion is natural, like natural fires occurring in forests and grasslands. Other combustion is caused by human activities. Anthropogenic combustion has altered the carbon cycle in the past 2 centuries. For example, forest fires are a natural occurence, but human management has increased the frequency of fires in some areas. In addition, human burning of fossil fuels introduces almost 10 to 100 times as much carbon per year to the atmosphere(about 10^{15} grams) as the slow carbon cycle (10^{13} to 10^{14} per year). Human alteration to the global carbon cycle is discussed further below.

For more explanation, watch this video "The Carbon Cycle" by the U.S. Environmental Protection Agency.



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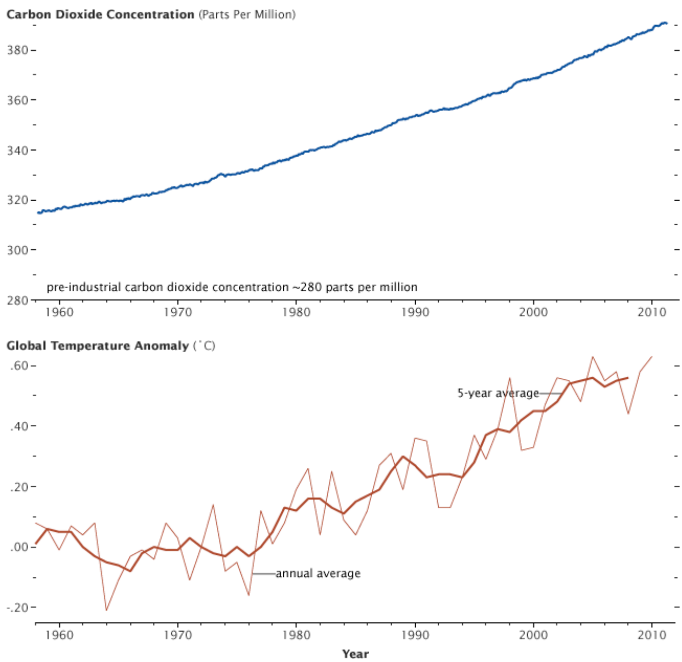
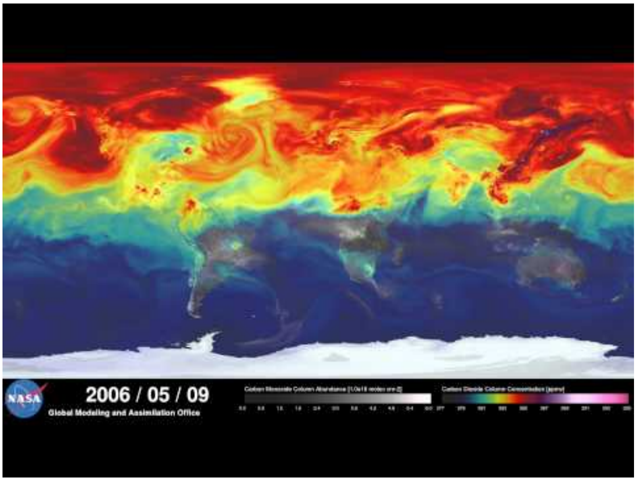
Human activities that alter and disrupt the carbon cycle

Extraction and combustion of fossil fuel

Over the past two centuries, extraction and combustion of fossil fuels (e.g., coal, oil, natural gas) has increased to meet energy demands. However, the combustion of fossil fuels releases a large amount of CO_2 into the atmosphere. CO_2 is a **greenhouse gas** that absorbs infrared radiation. Excessive amounts of CO_2 have caused our planet to become much warmer than it has been in a very long time and have altered patterns of precipitation, as discussed in the unit on climate change. In brief, many studies indicate that current CO_2 levels in our atmosphere fluctuate greatly have risen since the Industrial Revolution (see the blue graph below). During the same time, the mean temperature of the Earth has increased by about 0.8°C (see the red graph below). (Graphs by Robert Simmon, using CO_2 data from the NOAA Earth System Research Laboratory and temperature data from the Goddard Institute for Space Studies.)(Image source: NASA's Earth Observatory)



Importantly, carbon dioxide released from one particular area does not stay in the same area. Watch the NASA's video "A Year in the Life of Earth's CO_2" to learn about global CO_2 distribution on the earth and answer the following questions.



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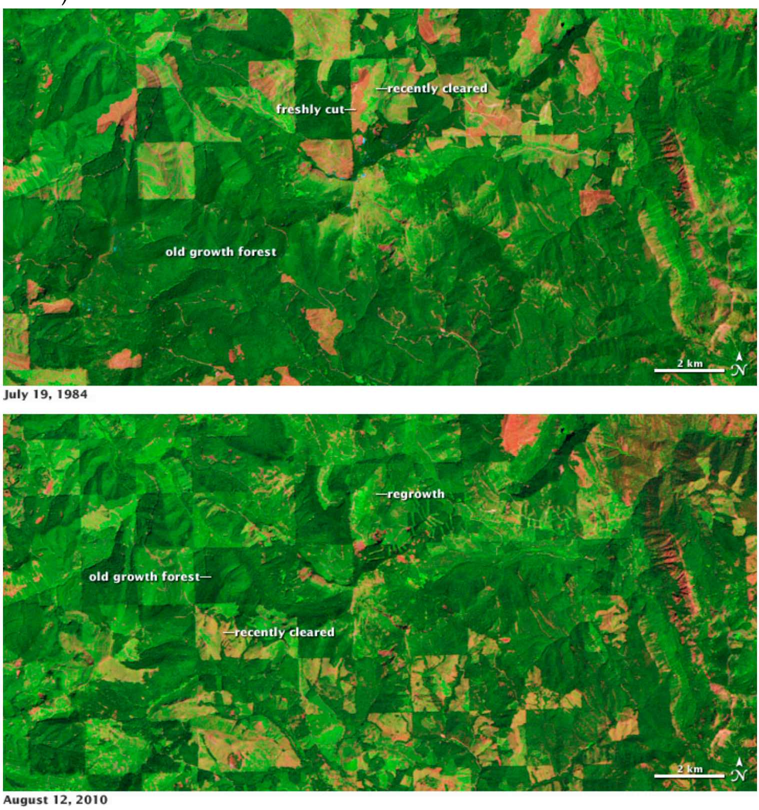
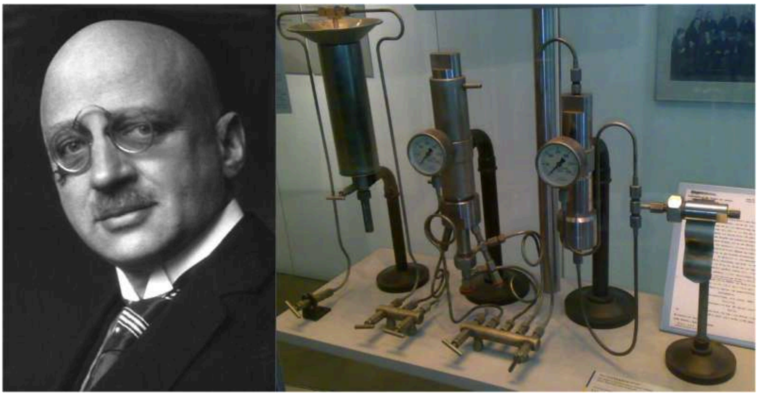
Deforestation

In the past several decades, humans have cleared forests to make land available for other uses including urban development and agriculture. The process of **deforestation** not only releases CO_2 from burning during clearing and the decomposition process of debris, but also reduces the amount of atmospheric CO_2 that can be absorbed by plants for photosynthesis by removing the vegetation. Time series of satellite data, like the imagery available from the Landsat satellites, allow scientists to monitor changes in forest cover. Deforestation can release carbon dioxide into the atmosphere, while forest regrowth removes CO_2. The pair of false-color images below shows clear-cutting and forest regrowth between 1984 and 2010 in Washington State, northeast of Mount Rainier. Dark green corresponds to mature forests, red indicates bare ground or dead plant material (freshly cut areas), and light green indicates relatively new growth. (NASA image by Robert Simmon, using Landsat data from the USGS Global Visualization Viewer.)



Introduction to the Nitrogen Cycle



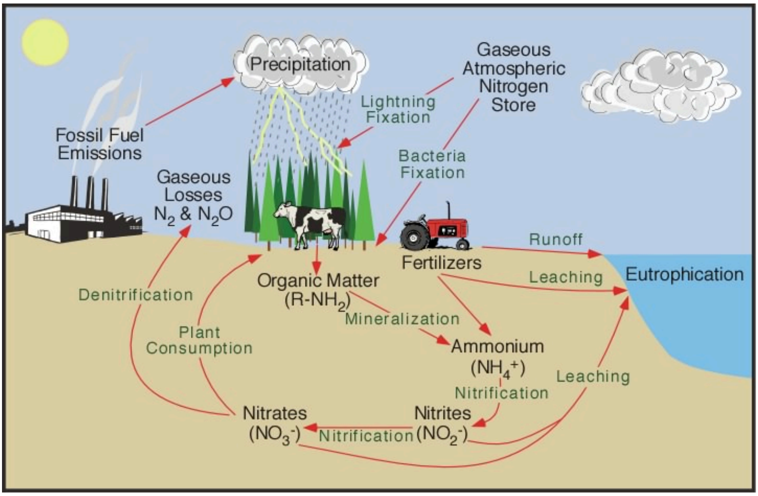
Nitrogen is essential to every living cell. In the atmosphere, nitrogen makes up 78% of the gas molecules by volume (as in forms of N_2 gas). Yet, most of animals and plants are not capable to access the nitrogen gas (unreactive) due the extradinary stability of the triple bond between the two nitrogen atoms. For hundrds of years humans have been limited to access fixed nitrogen until two German chemists Fritz Haber (shown on the left in the image above, credit: The Nobel Foundation, 1919) and Carl Bosch invented the **Haber-Bosch process**, an artificial nitrogen fixation process. The Haber-Bosch process is typically conducted with both nitrogen and hydrogen gases continuously passed through beds of catalyst under high pressure (15 – 25 MPa; equivalent to 2,200–3,600 psi) and high temperatures between 400–500 °C (752–932 °F) to produce ammonia gas (NH_3). The apparatus invented by Haber to create ammonia gas for the first time is shown on the right in the image above (Credit: JGvBerkel). Haber and Bosch were later awarded Nobel prizes in 1918 and 1931, respectively, for their invention of Haber-Bosch process.

The Haber-Bosch process made the production of chemical fertilizers possible. As the world's human population continued to grow rapidly in the early 20th century, the usage of fertilizers was urgently needed to provide better crop yield. The Haber-Bosch process provides a solution to "fix" unreactive nitrogen, which converts nitrogen from an inactive gas in the air to nitrogen compounds that would be further used to produce fertilizers for promoting crop yields. The Haber-Bosch process has changed how nitrogen fertilizers are produced and used in the modern society. It played a significant role and contributed to the success of the "Green Revolution" of the 20th century.

The Nitrogen (N) cycle

Nitrogen (N) is an important component to all life. Nitrogen makes up amino acids, which are the building blocks of protein and nucleic acids (i.e. DNA and RNA). Nitrogen in the atmosphere (or in the soil) can go through many complex chemical and biological changes to be combined into living and non-living materials. This is called the nitrogen cycle.

The largest **abiotic** reservior of nitrogen is the atmosphere. The atmosphere is 78 percent nitrogen gas (N_2), which is colorless, odorless, and nontoxic. However, getting this nitrogen into the living world is difficult. Plants and phytoplankton are not equipped to incorporate nitrogen gas from the atmosphere. Nitrogen gas exists as tightly bonded with a triple covalent bond, which is very hard to break. Because of this, many plants live in a world surrounded by nitrogen, but their growth is still limited by a lack of nitrogen they can use. Nitrogen moves through different abiotic and biotic reservoirs via five major processes (as shown below, credit: NOAA https://cpo.noaa.gov/Meet-the-Divisions/Earth-System-Science-and-Modeling/AC4/Improved-understanding-of-nitrogen-cycle). We will discuss each of these processes further.



Six processes that regulate the nitrogen cycle

Nitrogen fixation

Although 78 percent of atmospheric gas is nitrogen gas (N_2), most living organisms (including plants) cannot utilize nitrogen gas. Nitrogen enters the living world via **bacteria**, which incorporate nitrogen into their macromolecules (large molecules like carbohydrates and proteins) through **nitrogen fixation.** Biological nitrogen fixation is very energy-intensive process in which atmospheric nitrogen (N_2) is converted into forms that primary producers can use, including **ammonia** (NH_3) which is rapidly converted into **ammonium** (NH_4^+) in the presence of water. This ammonium "sticks" to clay particles in the soil because the clay particles generally have a negative charge. The ammonium can be taken up by plants or transformed further.

Nitrogen fixation can also occur when lightning, wildfires or combustion of fossil fuels converts nitrogen gas (N_2) into nitrate

(NO_3^-). Some nitrogen-fixing bacteria is found living in the root nodules of legumes, such as peanuts, and other plants. The plants provide sugar (from photosynthesis) to the bacteria and the bacteria provide nitrogen in a form the plant can use.

Nitrification

Nitrification is an important process in the nitrogen cycle, which can occur in soils, aquatic ecosystems, and wastewater treatment systems. During the nitrification process, ammonia (NH_3) is converted to **nitrate** (NO_3^-) through biological processes.

Nitrification is performed by two functionally defined groups of microbes (including bacteria and archaea), referred to together as **nitrifiers**.

The first functional group of nitrifiers is the **ammonia oxidizers**, which oxidize ammonium (NH_3) to **nitrite** (NO_2^-). Most bacteria that oxidize ammonia under aerobic conditions are chemoautotrophs and use the small amount of energy produced in these reactions to convert carbon dioxide into sugars.

$NH_3 \longrightarrow NO_2$

In particular, there are two main groups of bacteria: ***Nitrosomonas*** and ***Nitrosococcus*** bacteria, involved in this process, but recently, some species of Archaea, a group of organisms that are similar to bacteria but with structural and genetic differences, have been found to also oxidize ammonia.

The second functional group of nitrifying microbes is the **nitrite**-oxidizing bacteria, which convert nitrite (NO_2^-) to nitrate (NO_3^-).

$NO_2^- \longrightarrow NO_3^-$

The best-known cultivated members in this group are the ***Nitrobacter*** and ***Nitrococcus*** bacteria. These bacteria also derive a small amount of energy from this reaction, which they use to convert CO_2 into sugars. Because the energy released in this reaction is so small, the growth rate for these bacteria is also very small.

The overall chemical reactions involved in the nitrification process are summarized below.

$NH_4^+ \longrightarrow NO_2^- \longrightarrow NO_3^-$

Nitrate is also one of the nitrogen sources for many plant and algal groups and can be easily assimilated by producers. In contrast to ammonium, nitrate is more easily leached in the soil solution. Thus, nitrification can potentially reduce the efficiency of fertilizer application because the nitrogen can more easily be carried through the soil by water (leaching). Nitrate is also the substrate of the denitrification process (A process that returns fixed nitrogen compounds in the ecosystem back to inactive nitrogen gas in the atmosphere.). Nitrification process plays a critical role in the balance of nitrogen cycle.

Traditionally, scientists thought that all nitrification occurred in aerobic conditions, parts of the soil with oxygen, usually relatively near the surface. In 1999, scientists discovered another process anammox (anaerobic ammonia oxidation), which, as the name states, occurs in anaerobic conditions. This process was first discovered in wastewater treatment plants (where sewage is treated) but has since been discovered in a lot of aquatic systems. Because nitrification is a necessary step before denitrification, which returns nitrogen to the atmosphere, annamox may be an important process in nitrogen loss from aquatic systems.

Denitrification

During denitrification, nitrates (NO_3^-) in the soil or sediment (basically soil in an aquatic system) are converted into dinitrogen gas (N_2) and released back into atmosphere. The first main step, from nitrate to nitric oxide (NO) is accomplished by several groups of bacteria (e.g., *Pseudomonas denitrificans*) under anaerobic conditions. The denitrification process is important for a number of reasons. In agricultural systems, denitrification removes inorganic, plant-available nitrogen and returns it to the atmosphere, representing a decrease in effectiveness of fertilization. In wastewater treatment, denitrification is an important step because it decreases the amount of nitrogen that is discharged to surface waters. In addition, some of the intermediate products of denitrification are greenhouse gases.

Nitrate can also be converted into ammonium, through a process called dissimilatory nitrate reduction to ammonium (DNRA). DNRA is a particularly important process in low-oxygen marine ecosystems because it occurs in anaerobic conditions. It does not remove nitrate from the system, but instead converts it into another form useable for plants.

Assimilation

Assimilation is the process when primary producers take up inorganic NH_4^+ or NO_3^- from the soil, and incorporate it into their plant tissues as organic N compounds (such as amino acids, proteins and other N-containing compounds). Primary consumers **assimilate** nitrogen from primary producers and then excrete it as waste via metabolic processes.

The available supply of inorganic nitrogen to producers in the ecosystem is critical to the study of ecoysystem dynamics. Just as the amount of energy available in an ecosystem can limit the populations of higher trophic levels, the amount of nitrogen available often limits the growth of primary producers and therefore higher trophic levels.

The inorganic nitrogen (ammonia and nitrate) that is assimilated by plants is successively converted into organic nitrogen. This organic nitrogen is then returned to the atmosphere as nitrogen gas by three processes in terrestrial systems: **mineralization** (described below) then **nitrification** and **denitrification**.

Mineralization

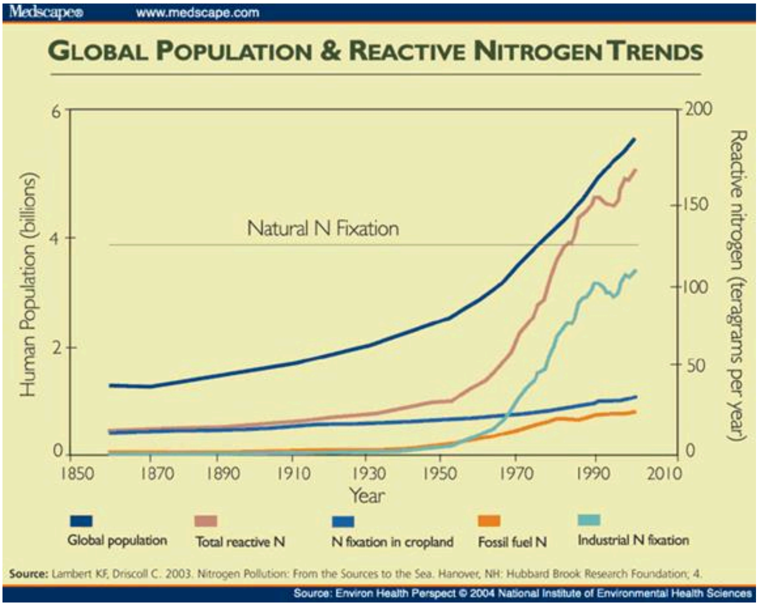
Consumers' nitrogenous waste and dead tissues of animals and plants are consumed and broken down by scavengers and detritivores first and further decomposed by bacterial and fungi (decomposers). **Mineralization** is the process of breaking down organic nitrogen compounds into inorganic nitrogen compounds (NH_4^+ or NO_3^-) by decomposers (i.e. bacteria and fungi) and releasing the nitrogen back to soils.

Human activities that alter and impact global nitrogen cycle

Human activities release nitrogen into the environment by two primary means: (1) the use of artificial fertilizers in agriculture, which are then washed into lakes, streams, and rivers by surface runoff; (2) the usage and combustion of fossil fuels, which releases different nitrogen oxides to the atmosphere. Fertilizer runoff is a major contributor to eutrophication. As described at the start of this section, the technology of manufacturing nitrogen-containing fertilizer by fixing atmospheric nitrogen gas was first developed by German chemists, Fritz Haber and Carl Bosch, during World War I. It is called **Haber-Bosch** process.

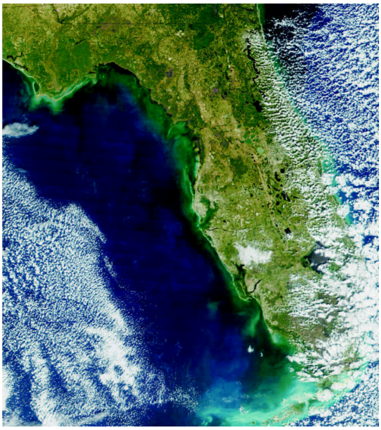
You can also listen to Radiolab podcast episide: "How do you solve a probelm like Fritz Haber?" to learn more about Fritz Haber.

The amount of fertilizer application is strongly correlated to growth of human population. The amount of industrially nitrogen-containing fertilizers applied to agricultural lands during 1980-1990 was more than all industrial fertilizers applied previously in human history. Approximately 100 million metric tons of nitrogen is fixed each year in the form of N fertilizers. Farmers also plant nitrogen-fixing crops to enhance soil nitrogen fertility. An estimated 40 million metric tons of N (ranges from 32-53 million metric tons) may be fixed annually by N-fixing agricultural and pastoral systems (e.g., soybeans, peas, beans, alfalfa, and rice paddies), which is not a part of natural N-fixation process (as shown below, Fields, 2004).



This chart above indicates the application of chemical fertilizers is strongly correlated to global human population growth. The input of total reactive nitrogen is contributed by industrial nitrogen fixation (fertilizer production), nitrogen fixing crop plants and fossil fuel combustion. (Image source: *Environmental Health Prospect*, 2004)

The excess nitrogen fertilizer input (along with excess phosphorus) to terrestrial ecosystems has caused the leaching and runoff of nitrogen (and phosphorus) into aquatic ecosystems and resulted in ***eutrophication***. Eutrophication is a process where nutrient runoff causes the excess growth of microorganisms (mainly algae).



The overgrown algal populations block sunlight, deplete dissolved oxygen levels and indirectly kill other flora and fauna in the aquatic ecosystems. Nitrogen fertilizer runoff contributes to the formation of algal blooms such as the red tide bloom in the image at left, which extended more than 100 miles along Florida's Gulf coastline in 2001. Such blooms kill thousands of fish and threaten human health. (Image source: Fields, *Environmental Health Prospect*, 2004)

b. Agricutural managment and fossil fuel combustion

There are an estimated 20 million metric tons of nitrogen in the form of **NO_x** (i.e. both NO and NO_2; NO- nitric oxide and NO_2 – nitrogen dioxide) and nitrous oxide (**N_2O**) released annually by high temperature combustion of fossil fuels from automobiles, factories, power plants, etc.

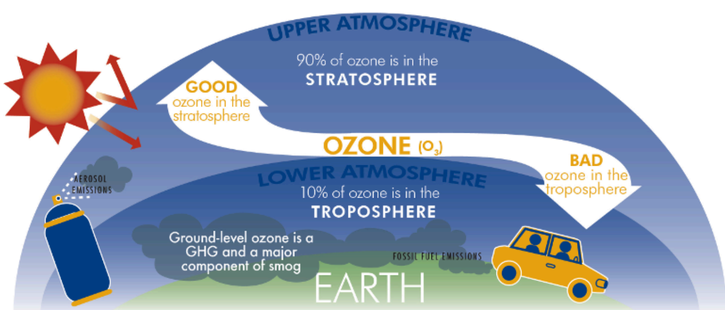
The NO_x and N_2O are derived from both the old N stored in fossil fuels or newly fixed nitrogen from the atmosphere.

The release of NO_x and N_2O into atmosphere can cause:

1. **Thinning stratospheric ozone** and **forming tropopsheric ozone**

Ozone (O_3) exists at a very low concentration in our atmosphere (about three molecules of ozone for every 10 million air molecules). Despite this small amount, ozone plays a vital role in the atmosphere. Ninety per cent of ozone resides in the **stratosphere**

layer, which extends between 10 – 17 kilometers above the Earth's surface and up to about 50 kilometers. The remaining 10% of ozone is located in the **troposphere**, which is the lower region of the atmosphere (10 – 17 km above the Earth's surface). Stratospheric ozone absorbs most of the damaging ultraviolet sunlight (i.e. UV-B) to only allow a small amount to reach the Earth's surface. Therefore, stratospheric ozone protects living organisms from the harmful impacts of excessive exposure to UV-B radiation. The diagram below shows how the ozone is distributed between stratosphere and troposphere layers. The ozone in stratosphere layer is often called "good ozone", because it prevents the damage of ultraviolet sunlight to living organisms on Earth by absorbing most of ultraviolet sunlight before it can reach the Earth's surface. However, the ozone formed in the troposphere is "bad ozone" due to it is one of the greenhouse gases (GHG) and its major contribution to the formation of smog. (Image source: The Field Museum, Chicago)



NO_x triggers a chemical reaction to break down "good" ozone. One oxygen atom (O) and one ozone molecule (O_3) are broken down to two oxygen gas molecules (O_2) with NO_x molecules involved but not used. This means that this ozone catalytic cycle can repeat many times as long as NOx (derived naturally or anthropogenically) is available in the stratosphere for reaction. The release of NO_x into the stratopshere can significantly remove ozone from the stratosphere, therefore expose living organisms to excess UV-B radiation.

<u>The formation of "bad" ozone in troposphere</u>

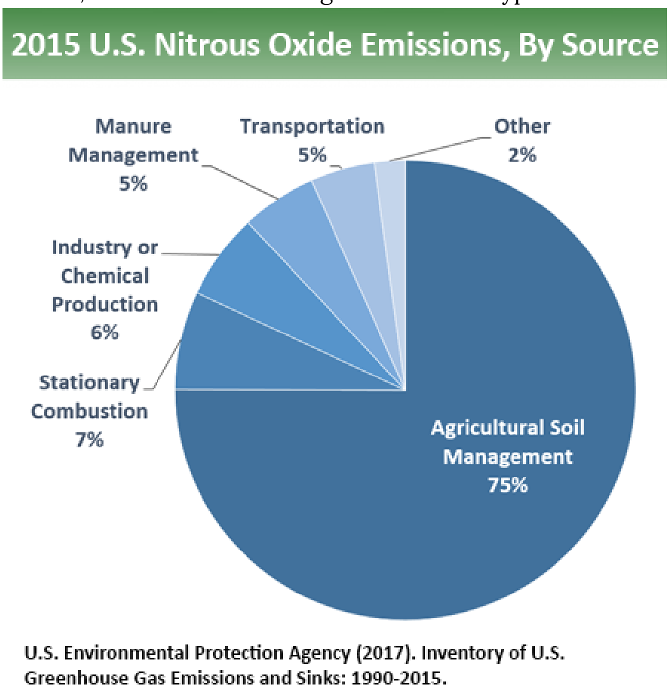
Low concentration of ozone occurs naturally in troposphere. Two natural sources of troposphere ozone are (1) released by plants and soil and (2) small amount of ozone migrated from stratopshere. The naturally occurred tropopshere ozone is not considered as a threat to human health and our enviornment due to its neglectable amount. However, tropospheric ozone has increased due to certain human activities. When sunlight (particulaly ultraviolet light), hydorcarbons and nitrogen oxides (NO_x) emitted from automobiles, refineries and fossil fuel power plants interacts, it has doubled the ozone in the troposphere since 1900.

When tropospheric ozone reaches high levels and cause **smog** pollution (Smog is the air pollution that is composed of many air pollutants, including nitrogen oxides, sulphur oxides, ozone, smoke or other particulates (such as carbon monoxide and CFC), it could pose a threat to people with respiratory problems, tissue decay and other healthy issues. That's why the tropospheric ozone is called "bad ozone" (Figure 17.9).

2. **Global warming** (N_2O is one of the greenhouse gases.)

The atmospheric concentration of **nitrous oxide (N_2O)** has been reported to be increasing in the past decades. Increased nitric oxide in the atmosphere has led to concern because it is one of the greenhouse gases. Nitrous oxide is naturally present in the atmosphere as part of global nitrogen cycle. However, many human sources, such as agriculture, fossil fuel combustion and industrial processes, have increased atmospheric nitrous oxide concentrations (ca. 40% of global total N_2O emission) in the past decades. The pie chart below shows the sources of nitrous oxide (N_2O) emission in the United States. All emission estimates from the U.S. Greenhouse Gas Emissions and Sinks: 1990-2015. (Credit: United States Environmental Protection Agency)

Agricultural management and practices are the largest source of N_2O emissions in the United States. It accounts for 75 percent of total U.S. N_2O emissions in 2015. Five percent of nitrous oxide is also emitted from livestock manure and urine. Nitrous oxide is also emitted when burning fossil fuel. The type of fuel and combustion technology and practice can affect the amount of N_2O emitted from the combustion. During the industrial processes to produce synthetic commercial fertilizers, nylon and other synthetic products, nitrous oxide is also generated as a byproduct.

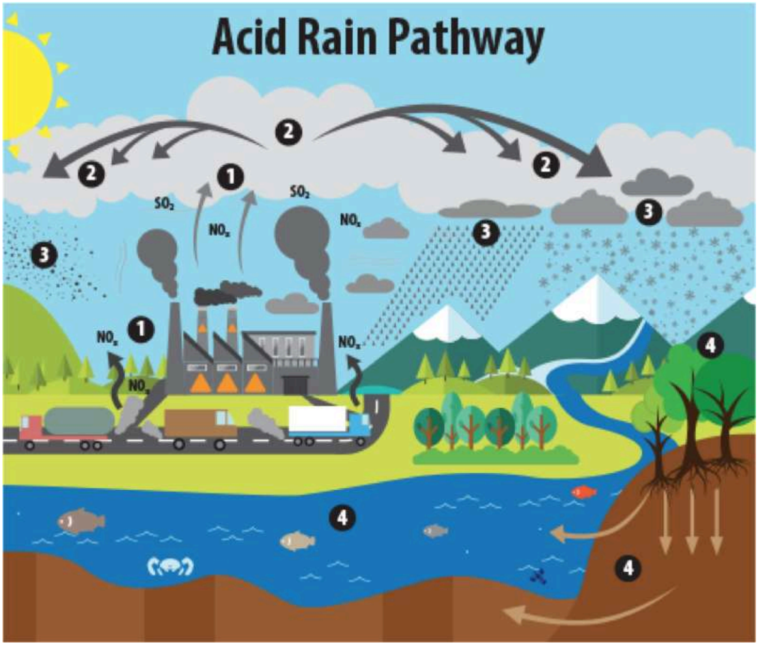


Nitrous oxide is a powerful greenhouse gas with a global warming potential of 298 times that of carbon dioxide (CO_2), which means the impact of 1 pound of N_2O on warming the atmosphere is 298 times that of 1 pound of carbon dioxide. Because of the emission control standards for vehicles and mobiles, nitrous oxide emissions in the United States have decreased by about 7 percent between 1990 and 2015. This is contributed to a decreased emission from mobile combustion, however, nitrous oxide emissions from agricultural sources were only about 2 percent lower in 2015 than in 1990.

3. **Air pollution and acid precipitation**

Acid rain is partially caused by nitrogen oxides (NO_x) and sulfur dioxide (SO_2) in the atmosphere that is transported by wind and air currents. The atmospheric NO_x (and SO_2) can form nitric acids and sulfuric acids, respectively, when reacting with water, oxygen and other chemicals in the atmosphere before falling to the ground. Even though natural sources (such as volcanic eruption) contribute some NO_x into the atmosphere, the majority of NO comes from human activities.

The major of NO_x in the atmosphere are derived from burning of fossil fuels (for generating electricity) and fuel emission from vehicles and heavy equipment, manufacturing, oil refineries and other industries. The image below illustrates the pathway for acid rain in the environment: (1) Emission of SO_2 and NO_x are released into the air, where (2) the pollutants are transformed into acid particles that may be transported long distances. (3) These acid particles then fall to the earth as wet and dry deposition (dust, rain, snow, etc.) and (4) may cause harmful effects on soil, forests, streams and lakes. (Image source: Acid Rain Pathway by United States Environmental Protection Agency)



Introduction to Phosphorus Cycle

Both phosphorus and nitrogen are essential nutrients for the plants and animals that make up terrestrial and aquatic food webs. In particular, phosphorus is in short supply in many fresh waters and coastal marine ecosystems. While an insufficient phosphorus supply can cause stress to plants and vegetation, with a modest amount of increase in phosphorus can accelerate phytoplankton growth (algal blooms). Such algae overgrowth could result in reduced water clarity, water quality and limited light penetration. The die-offs of dense algal blooms can speed up microbial decomposition to deplete dissolved oxygen in the water and create "**dead zone**" in the aquatic ecosystems. A lack of sufficient dissolved oxgyen causes the death of many fish, invertebrates, and other aquatic organisms. Dead zones are found in many freshwater lakes, for example, the central basin of Lake Erie of the Great Lakes in the United States.

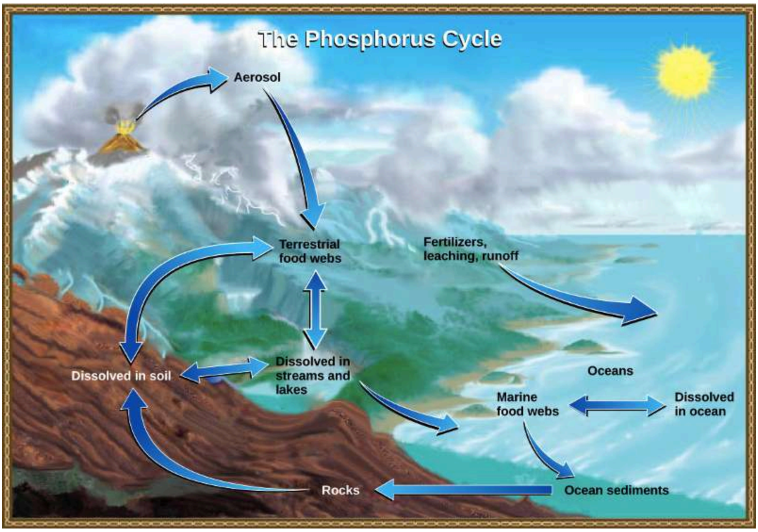
There are natural and anthropogenic sources for phosphorus. The natual sources include phosphorus stored in soils and rocks. However, many sources of phosphorus are derived from human activities, including failing wastewater treatment plants and septic systems and runoff from fertilized cropland and animal manure storage areas. In this section, we will learn about the geochemical processes that regulate the global phosphorus cycle and further discuss the impacts of human activities on the global phosphorus cycle.

The Phosphorus (P) Cycle

Phosphorus (P) is an essential nutrient for living organisms and all living processes. It is a major component of nucleic acids (DNA and RNA), ATPs and phospholipids on cell memebranes. As calcium phosphate ($CaPO_4^{3-}$), phosphorus also makes up supportive components of our bones. Phosphorus is often the limiting nutrient (A limiting nutrient here implies that the nutrient may be difficult for a plant to acquire, and therefore it becomes the only nutrient that is limiting the plant's growth.) in aquatic ecosystems, because its low concentration of dissolved phase in fresh water and marine ecosystem. Unlike carbon and nitrogen, phosphorus does not have a gas phase, and it can only enter the atmosphere in the form of dust. Phosphorus occurs in nature and moves in the form of **phosphate ion** (**PO_4^{3-}**). Due to the short supply of phosphate in nature, the vast majority of phosphorus compounds in the rocks and sediments are extracted for the production of fertilizers to promote plant growth.

18.1 Five processes that regulate the global phosphorus cycle

Phosphorus is released through natural surface runoff when leaching from phosphate-containing rock (a process called **weathering**). The leached phosphorus, thus, is drained into fresh water ecosystems (including rivers and lakes) and the ocean. The phosphate-containing rock has its origins in the ocean, which is formed primarily by the bodies and excretions of ocean organisms and from inorganic sediments. However, in remote regions, volcanic ash, aerosols, and mineral dust may also be the significant phosphate sources. The sediment deposited at the bottom of the ocean then is uplifted and become land areas of the Earth's surface over geologic time (**tectonic lifting**). Phosphorus is also reciprocally exchanged between dissolved phosphate in the ocean and organic phosphate stored in the food webs of marine ecosystems (**Figure 18.2**). The movement of phosphate from the ocean to the land and through the soil is extremely slow, with an average oceanic residence time between 20,000 and 100,000 years.



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

We will discuss the following five major processess that regulate global phosphorus cycle.

1. Tectonic lifting:

Tectonic lifting is the uplifting process of the phosphate rocks (such as metamorphic, sedimentary, and igneous rocks) slowly by geological forces to become land surface and mountains. It marks the beginning of the global phosphorus cycle. Rates of tectonic lifting can range from zero to approximately 8 meter per thousand years (Buendía et al. 2010)

2. Weathering:

During the process of soil development, phosphorus in the uplifted rocks can be broken down and released into soils, a process called **weathering**. The phosphorus-containing rocks can be physically and chemically weathered by wind and rain (abiotic force), as well as penetration of plant roots and activities of other living organisms (biotic force). The weathering process requires water (H_2O) and carbon dioxide (CO_2). Carbon dioxide is normally existed in sufficient concentations in the soil environment. Therefore, rates of weathering reactions are strongly depending on the availability of water (soil moisture) and other factors, including annual temperature and content and structure of weathering materials (Buendia et al. 2010). The weathering process contributes phosphate ions into the lands and terrestrial ecosystems. Phosphate eventually makes it back to the ocean via surface runoff and leaching.

3. Assimilation

Assimilation is the process that occurs when primary producers (i.e. plants and algae) take up phosphate (PO_4^{3-}) and incorporate it into their living tissues. It also includes when consumers assimilate phosphorus from primary producers or their preys. Some of phosphorus that is not assimilated into living tissue will be excreted as waste. Some plant species have a long-term established symbiotic relationship with mycorrhizae (one type of fungi), especially in ecosystems with low supply of phosphorus. Because phosphate in the rock normally hold the phosphorus in very insoluble forms, the ability of mycorrhizal fungus to produce organic acids can help release some soluble phosphorus and make it availability for plants. Mycorrhizal fungi help locate and absorb phosphate ions in the soil for their host plants, which they receive carbonhydrate (such as glucose and sucrose) as energy sources in return.

4. Mineralization:

The **mineralization** is the process that organic phosphorus compounds in the living organisms are converted into inorganic phosphate ions (PO_4^{3-}) by the decomposers, which then released back to soils for plants to use. Phosphorus compounds from animal excretion of urine and dead animal/plant tissues are consumed and broken down by scavengers and detritivores first, then organic phosphorus compounds are later converted to inorganic PO_4^{3-} ions by phosphatizing bacteria and fungi (decomposers).

5. Precipitation:

Phosphorus loss from terrestrial ecosystems is often through land surface runoff and erosion, drainage, fire, and artificial removal due to human activities (mining). When available inorganic phosphorus can react with dissolved minerals (such as iron, aluminum, manganese, or calcium) to form phosphate minerals that are not avaiable to plant uptake, it is called **precipitation**. In oxygenated waters, phosphorus precipitates after binding with calcium and iron [e.g., calcium phosphate, $Ca(H_2PO_4)_2$]. While under the low-oxygen condition, dissolved iron binds with sulfur instead of phosphorus, making phosphorus more available to plants.

18.2 Human activities that alter and impact the global phosphorus cycle

1. Phosphate mining for production of fertilizer:

There is no atmospheric stage for the phosphorus cycle. Therefore, rock phosphate is mined from naturally occurring deposits for fertilizer production, animal feeds, and agricultural crops. Phosphate is usually found in shallow, near shore marine environments due to accumulation in ocean sediments / reefs and flushing from river systems into bays.

The largest known deposit of phosphorus in the United States is in Bone Valley, Florida. The Bone Valley Formation is a geologic formation in Florida, which contains economically important phosphorite deposits in west-central Florida, as well as rich assemblages of vertebrate fossils. At the current rate of consumption, the supply of phosphorus is estimated to run out in 345 years.

2. Eutrophication and dead zones

The practice of phosphorous mining has increased the amount of phosphorus released into the soils. When excess phosphorus (and nitrogen) (drained from fertilizer runoff and sewage) enters the aquatic ecosystems, it causes harmful effects to the ecosystem, i.e. eutrophicatio. **Eutrophication** is the process where excess phosphorous and nitrates contribute to an increase in productivity of phytoplankton populations (mostly algae), leading to excessive growth of microorganisms within aquatic systems. The photo below shows the eutrophication in Lake Dora, Florida, which is covered in algal blooms. (Image credit: Nation Ocean Service. National Oceanic and Atmospheric Administration, U.S. Department of Commerce.). Eutrophication is discussed in more detail in the introduction to this part of the textbook.

Connection: Nutrient loading in Lake Erie (Great Lakes Area)

Part of the earth's largest surface freshwater system, Lake Erie is a vital source of drinking water for 11 million people. Researchers Anna Michalak, Tom Bridgeman, and Pete Richards are studying how farming practices and severe weather can increase the amount of fertilizer-derived nutrients in the water, which diminishes water quality and threatens the lake's ecosystem and the public's health. (Video source: National Science Fundation)

Watch the video: Nutrient Loading In Lake Erie for better understanding the mechanisms and consequence of eutrophication caused by human activities.

A YouTube element has been excluded from this version of the text. You can view it online here: https://viva.pressbooks.pub/theecosphereandenvironmentalissues/?p=136

Connection: Eutrophication in Atlanta, Georgia Area

Eutrophication has been a serious problem in the Atlanta, Georgia area. West Point Lake, which is south of the city, is the major lake that receives Atlanta's waste water. Sources of phosphorus pollution in the West Point Lake include mainly point sources, primarily from waste water treatment facilitiesin metorpolitan Atlanta. West Point

Lake had been observed with excess algal growth. From the 1940s to 1990s, household detergents contained phosphates in order to improve their cleaning effectiveness. However, these phosphates travelled into natural systems through wastewater and contributed to eutrophication and dead zones described above.

The chart below (**Figure 18.8**) shows the measurement of the amount of phosphorus (in tons per year) in upstream and downstream of the Chattahoochee River at Atlanta (Chattahoochee River is a major source of the water supply for Atlanta area.). Since 1990s, state laws has installed voluntary and mandatory restrictions on phosphorus detergents in the city to restrict phosphorus released from wastewater-treatment facilities. Most of household detergents now are phosphate-free! The amounts of phosphorus downstream of the city have decreased about 77% from the highest levels in 1984. It has caused large reductions in the amounts of phosphorus in the Chattahoochee River south of Atlanta, Georgia and in West Point Lake. Although, the total phosphorus load in the agricultural area north of town (upstream) continues to increase. What can we do?

Connection: Brainstorm the causes of increased phosphorus loads in the upstream portion of the Chattahoochee River. Additionally, come up with some potential solutions to reduce the amount of phosphorus being added to the river.

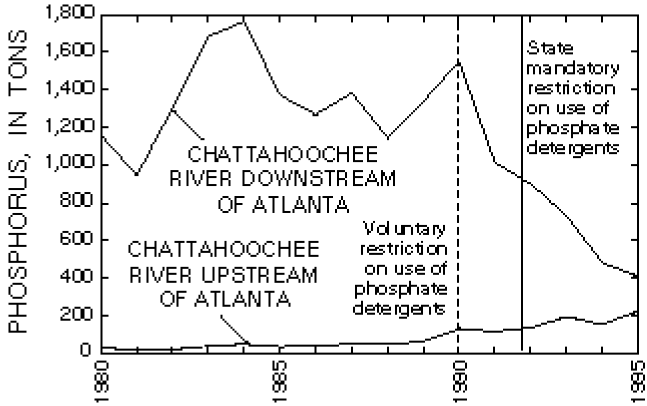


Figure 18.8. This chart shows the amount of phosphorus, in tons per year, upstream and downstream of the Chattahoochee River at Atlanta, which is a major source of the local water supply. Credit: U.S. Geological Survey, Department of the Interior/USGS. (URL: https://water.usgs.gov/edu/phosphorus.html)

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Figure 18.1 (left) Sampling Lago de Pátzcuaro during a cyanobacterial bloom with Ilyana Berry, Dr. John Berry, and Dr. Fernando Bernal-Brooks. © 2013 Nature Education Photo by Alan Wilson. All rights reserved. Copyright notice: https://www.nature.com/scitable/viewTermsOfUse

Figure 18.1 (right) "A dead African buffalo (Syncerus caffer) found in a reservoir with a dense bloom of the toxic cyanobacterium Microcystis at the Loskop Dam Nature Reserve in South Africa". © 2013 Nature Education Photo by Jannie Coetzee. All rights reserved. Copyright notice: https://www.nature.com/scitable/viewTermsOfUse

Figure 18.3 " Phosphogypsum stack ". Wikimedia Commons. Copyright: Harvey Henkelman.

Figure 18.4 " Discolored water ". Image credit: Nation Ocean Service. National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Public Domain.

Figure 18.5 "Eutrophication". Image source: Utah Department of Environmental Quality.

Figure 18.6 " The Dead Zone ". Image credit: the NASA Mississippi Dead Zone web site. National Aeronautics and Space Administration.

Video: Nutrient Loading In Lake Erie by National Science foundation. (Standard YouTube License).

Figure 18.8 " Phosphorus charts of the Chattahoochee River at Atlanta ". Credit: U.S. Geological Survey, Department of the Interior/ USGS. (URL: https://water.usgs.gov/edu/phosphorus.html)

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Figure 17.1 (left) " Chemist Fritz Haber ". Credit: The Nobel Foundation, 1919. Public domain. Created and published in 1919 in Sweden in Les Prix Nobel 1918 (p. 120).

Figure 17.1 (right) " The setup used by Fritz Haber to create ammonia for the first time " Public domain. Credit: JGvBerkel – Jewish Museum Berlin.

Figure 17.2 " Nitrogen Cycle " by U.S. Environmental Protection Agency. Public Domain.

Figure 17.3 (left) " Legumes " by Keith Weller, Agricultural Research Service, USDA. Public Domain.

Figure 17.3 (right) " Soybean root nodules " by JoJan, United States Department of Agriculture . Public Domain.

Figure 17.4 " Diagram of nitrogen assimilation ". Created by: Joshua Dingomal. Diagram source: www.bbc.co.uk. Modification by Ching-Yu Huang.

Figure 17.5 " Diagram of nitrogen mineralization ". Created by: Joshua Dingomal. Diagram source: www.bbc.co.uk. Modification by Ching-Yu Huang.

Figure 17.6 " Denitrification reaction sequence ". Image source: USGS. Adopted from https://wwwbrr.cr.usgs.gov/projects/EC_biogeochemistry/Cape.htm. Public Domain.

Figure 17.7 " Global Nitrogen: Cycling out of Control". by Scott Fields. *Global Nitrogen: Cycling out of Control* . Environmental Health Prospect, 2004,112(10). Open access article. (Copying and redistribution of this article are permitted in all media for any purpose) (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1247398/accessed 6/8/17)

Figure 17.8 "A rising tide." Credit: Scott Fields. *Global Nitrogen: Cycling out of Control.* Environmental Health Prospect, 2004,112(10). Open access article. (Copying and redistribution of this article are permitted in all media for any purpose) (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1247398/accessed 6/8/17)

Figure 17.9 " Ozone in stratosphere and troposphere layers ". Image source: The field museum, Chicago.

Figure 17.10 " 2015 nitrous oxide emission by sources pie chart " from the U.S. Greenhouse Gas Emissions and Sinks: 1990-2015. Credit: United States Environmental Protection Agency. Public Domain.

Figure 17.11 " Acid Rain Pathway ". Image source: United States Environmental Protection Agency. Public Domain.

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The Carbon Cycle is adapted from an ecology module edited and developed by Dr. Ching-Yu Huang, Biology instructor, Virginia Commonwealth University, VA.

This Open Educational Resource (OER) was generously funded through an “Affordable Learning Georgia” grant. Foundational content was derived from the OpenStax Biology text. The original text can be downloaded for free at: http://cnx.org/content/col11448/latest/

This new version, Introduction to Ecology, may be downloaded for free at: https://oer.galileo.usg.edu/biology-ancillary/7/

PART IV
DECLINING BIODIVERSITY

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

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

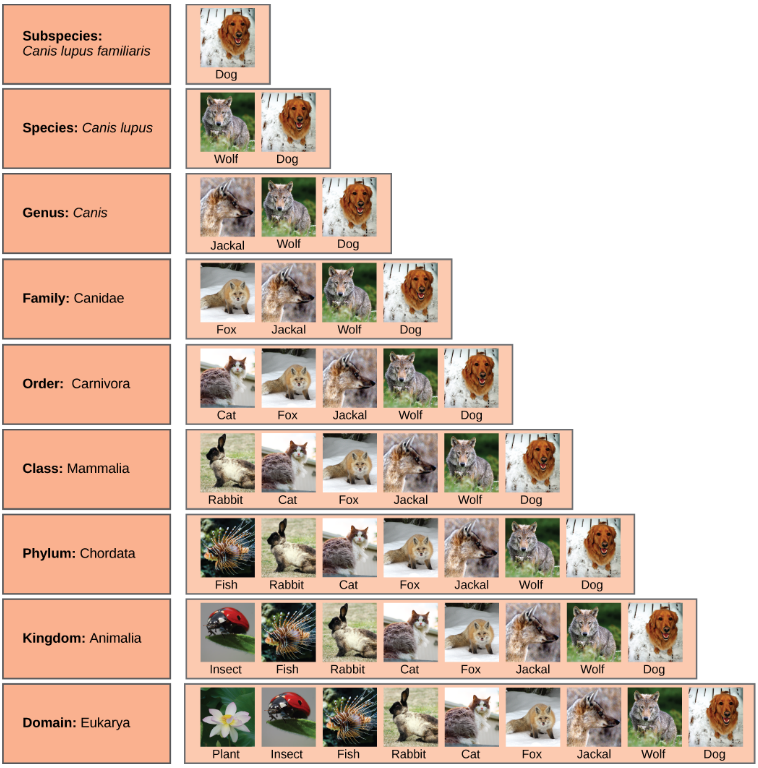

Figure 1. This illustration shows the taxonomic groups, in sequence, with examples. This illustration by OpenStax is licensed under CC BY 4.0

Domain Bacteria

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

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

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

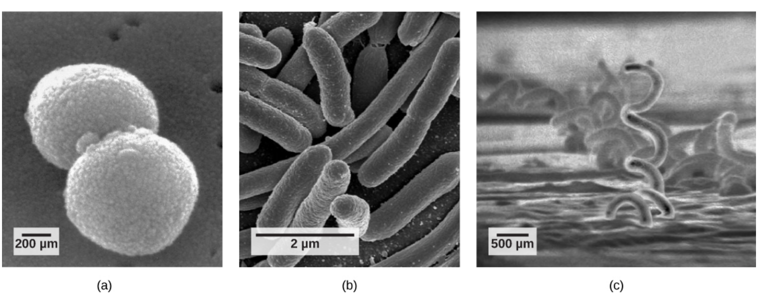

Figure 2. Many prokaryotes fall into three basic categories based on their shape: (a) cocci, or spherical; (b) bacilli, or rod-shaped; and (c) spirilla, or spiral-shaped. (credit a: modification of work by Janice Haney Carr, Dr. Richard Facklam, CDC; credit c: modification of work by Dr. David Cox, CDC;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

Domain Archaea

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

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

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

Domain Eukarya

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

Kingdom is the taxonomic grouping immediately below domain (see Figure 1).

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

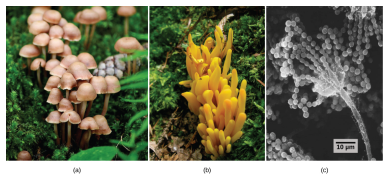

Figure 3. The (a) familiar mushroom is only one type of fungus. The brightly colored fruiting bodies of this (b) coral fungus are displayed. This (c) electron micrograph shows the spore-bearing structures of Aspergillus, a type of toxic fungi found mostly in soil and plants. (credit a: modification of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

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

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

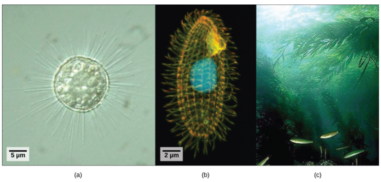

Figure 4. Protists range from the microscopic, single-celled (a) Acanthocystis turfacea and the (b) ciliate Tetrahymena thermophila to the enormous, multicellular (c) kelps (Chromalveolata) that extend for hundreds of feet in underwater "forests." (credit a: modification of work by Yuiuji Tsukii; credit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

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

Attribution

7. The Importance of Biodiversity

The Biodiversity Crisis

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

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

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

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

Types of Biodiversity

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

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

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

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

Current Species Diversity

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

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

Estimated Numbers of Described and Predicted species						
	Source: Mora et al 2011		**Source: Chapman 2009**		**Source: Groombr and Jenkins 2002**	
	Described	Predicted	Described	Predicted	Described	Predi
Animals	1,124,516	9,920,000	1,424,153	6,836,330	1,225,500	10,82
Photosynthetic protists	17,892	34,900	25,044	200,500	—	—
Fungi	44,368	616,320	98,998	1,500,000	72,000	1,500,
Plants	224,244	314,600	310,129	390,800	270,000	320,0
Non-photosynthetic protists	16,236	72,800	28,871	1,000,000	80,000	600,0
Prokaryotes	—	—	10,307	1,000,000	10,175	—
Total	1,438,769	10,960,000	1,897,502	10,897,630	1,657,675	13,24

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

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

8. Threats to Biodiversity

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

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. Human destruction of habitats (**habitat** generally refers to the part of the ecosystem required by a particular species) accelerated in the latter half of the twentieth century.

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

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

BIOLOGY IN ACTION: Preventing Habitat Destruction with Wise Wood Choices

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

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

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.

Attribution

9. Preserving biodiversity

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

Change in Biodiversity through Time

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

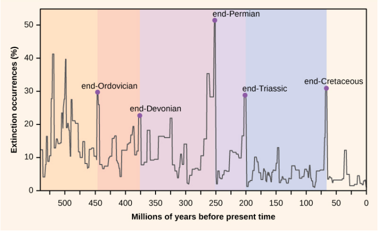

Figure 1. Extinction intensity as reflected in the fossil record has fluctuated throughout Earth's history. Sudden and dramatic losses of biodiversity, called mass extinctions, have occurred five times.

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

Recent and Current Extinction Rates

Many biologists say that we are currently experience a sixth mass extinction and it mostly has to do with the activities of humans. There are numerous recent extinctions of individual species that are recorded in human writings. Most of these are coincident with the expansion of the European colonies since the 1500s.

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

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

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

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

Estimates of Present-day Extinction Rates

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

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

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

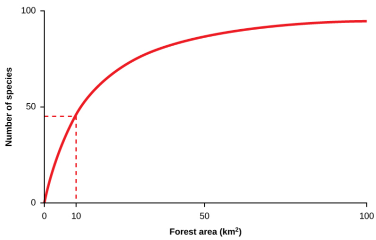

Figure 3. A typical species-area curve shows the cumulative number of species found as more and more area is sampled. The curve has also been interpreted to show the effect on species numbers of destroying habitat; a reduction in habitat of 90 percent from 100 km2 to 10 km2 reduces the number of species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

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

Conservation of Biodiversity

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

Changing Human Behavior

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

Link to Learning: Go to this website for an interactive exploration of endangered and extinct species, their ecosystems, and the causes of their endangerment or extinction.

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

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

Global warming is expected to be a major driver of biodiversity loss. Many governments are concerned about the effects of anthropogenic global warming, primarily on their economies and food resources. Because greenhouse gas emissions do not respect national boundaries, the effort to curb them is international. The international response to global warming has been mixed. The **Kyoto Protocol**, an international agreement that came out of the United Nations Framework Convention on Climate Change that committed countries to reducing greenhouse gas emissions by 2012, was ratified by some countries, but spurned by others. Two countries that were especially important in terms of their potential impact that did not ratify the Kyoto protocol were the United States and China. Some goals for reduction in greenhouse gasses were met and exceeded by individual countries, but, worldwide, the effort to limit greenhouse gas production is not succeeding. A renegotiated 2016 treaty, called the **Paris Agreement**, once again brought nations together to take meaningful action on climate change. But like before, some nations are reluctant to participate. The newly-elected President Trump has indicated that he will withdraw the United States' support of the agreement.

Conservation in Preserves

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

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

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

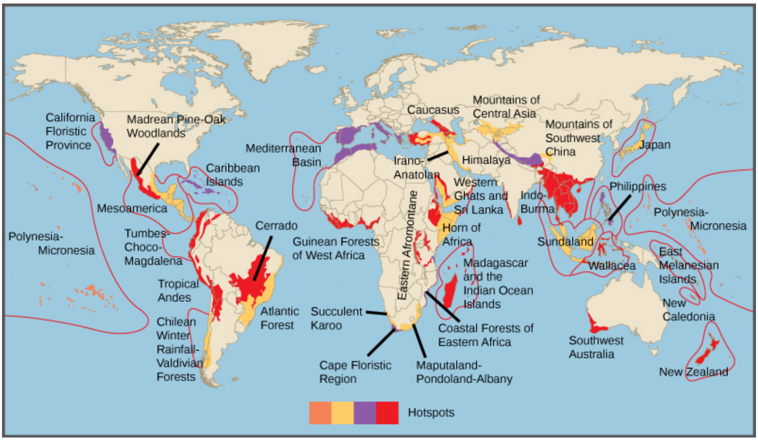

Figure 5. Conservation International has identified 34 biodiversity hotspots. Although these cover only 2.3 percent of the Earth's surface, 42 percent of the terrestrial vertebrate species and 50 percent of the world's plants are endemic to those hotspots.

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

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

Link to Learning: Check out this interactive global data system of protected areas. Review data about specific protected areas by location or study statistics on protected areas by country or region.

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

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

Habitat Restoration

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

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

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

The Role of Zoos and Captive Breeding

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

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

Suggested Supplemental Reading:

Paterniti. 2017. Should we Kill Animals to Save Them? *National Geographic*. October.

Quammen. 2019. Saving Africa's Parks. *National Geographic*. December

PART V

FOOD AND WATER FOR A GROWING POPULATION

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

From Agriculture to Food Security

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

Food security

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

When food security is analyzed at the national level, an understanding not only of national production is important, but also of the country's **access** to food from the global market, its foreign exchange earnings, and its citizens' consumer choices. Food security analyzed at the household level is conditioned by a household's own food production and household members' ability to purchase food of the right quality and diversity in the market place. However, it is only at the individual level that the analysis can be truly accurate because only through understanding who consumes what can we appreciate the impact of sociocultural and gender inequalities on people's ability to meet their nutritional needs.The definition of food security is often applied at varying levels of aggregation, despite its articulation at the individual level. The importance of a pillar depends on the level of aggregation being addressed. At a global level, the important pillar is food **availability**. Does global agricultural activity produce sufficient food to feed all the world's inhabitants? The answer today is yes, but it may not be true in the future given the impact of a growing world population, emerging plant and animal pests and diseases, declining soil productivity and environmental quality, increasing use of land for fuel rather than food, and lack of attention to agricultural research and development, among other factors.

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

When food security is analyzed at the national level, an understanding not only of national production is important, but also of the country's access to food from the global market, its foreign exchange earnings, and its citizens' consumer choices. Food security analyzed at the household level is conditioned by a household's own food production and household members' ability to purchase food of the right quality and diversity in the market place. However, it is only at the individual level that the analysis can be truly accurate because only through understanding who consumes what can we appreciate the impact of sociocultural and gender inequalities on people's ability to meet their nutritional needs.

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

Obesity

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

Figure 1. Obesity and undernourishment by region.

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

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

Suggested Supplementary Reading:

McMillan, T. 2018. How China Plans to Feed 1.4 Billion Growing Appetites. *National Geographic*. February.

Attribution

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

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

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

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

Water Reservoirs and Water Cycle

Water is the only common substance that occurs naturally on earth in three forms: solid, liquid and gas. It is distributed in various locations, called water reservoirs. The oceans are by far the largest of the reservoirs with about 97% of all water but that water is too saline for most human uses (Figure 1). Ice caps and glaciers are the largest reservoirs of fresh water but this water is inconveniently located, mostly in Antarctica and Greenland. Shallow groundwater is the largest reservoir of usable fresh water. Although rivers and lakes are the most heavily used water resources, they represent only a tiny amount of the world's water. If all of world's water was shrunk to the size of 1 gallon, then the total amount of fresh water would be about 1/3 cup, and the amount of readily usable fresh water would be 2 tablespoons.

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

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

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

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

Primary Fresh Water Resources: Precipitation

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

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

Surface Water Resources: Rivers, Lakes, Glaciers

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

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

Figure 5. Groundwater Seepage. Groundwater seepage can be seen in Box Canyon in Idaho, where approximately 10 cubic meters per second of seepage emanates from its vertical headwall. Source: NASA

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

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

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

Figure 7. Mountain Glacier in Argentina Glaciers are the largest reservoir of fresh water but they are not used much as a water

resource directly by society because of their distance from most people. Source: Luca Galuzzi – www.galuzzi.it

Groundwater Resources

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

Other sources of groundwater include seepage from surface water (lakes, rivers, reservoirs, and swamps), surface water deliberately pumped into the ground, irrigation, and underground wastewater treatment systems (septic tanks). **Recharge areas** are locations where surface water infiltrates the ground rather than running into rivers or evaporating. Wetlands, for example, are excellent recharge areas. A large area of sub-surface, porous rock that holds water is an aquifer. Aquifers are commonly drilled, and wells installed, to provide water for agriculture and personal use.

Water Use in the U.S. and World

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

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

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

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

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

Attribution

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7.2 Water Supply Problems and Solutions **Water Supply Problems: Resource Depletion**

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

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

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

Water Supply Crisis

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

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

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

Sustainable Solutions to the Water Supply Crisis?

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

Figure 3. Hoover Dam, Nevada, U.S. Hoover Dam, Nevada, U.S.. Behind the dam is Lake Mead, the largest reservoir in U.S.. White band reflects the lowered water levels in the reservoir due to

drought conditions from 2000 – 2010. Source: Cygnusloop99 at Wikimedia Commons

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

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

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

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

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

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

Suggested Supplementary Reading:

Weiss, K.R. 2018. Drying Lakes. *National Geographic.* March. p. 108-133.

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

Attribution

10. Population growth

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

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

Population Size and Density

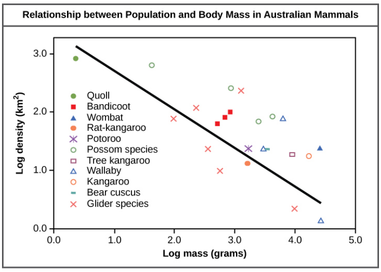


Figure 1. Australian mammals show a typical inverse relationship between population density and body size. As this graph shows, population density typically decreases with increasing body size. Why do you think this is the case?

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

Estimating Population Size

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

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

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

Using our example, the equation would be:

(80 x 100)/20 = 400

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

Species Distribution

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

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

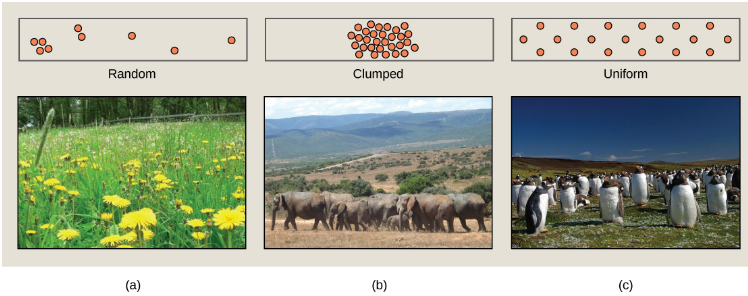


Figure 2. Species may have a random, clumped, or uniform distribution. Plants such as (a) dandelions with wind-dispersed seeds tend to be randomly distributed. Animals such as (b) elephants that travel in groups exhibit a clumped distribution. Territorial birds such as (c) penguins tend to have a uniform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

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

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

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

Life Table of Dall Mountain Sheep[1]

Age interval (years)	Number dying in age interval out of 1000 born	Number surviving at beginning of age interval out of 1000 born	Mortality rate per 1000 alive at beginning of age interval	Life mea rem atta
0–0.5	54	1000	54.0	
0.5–1	145	946	153.3	
1–2	12	801	15.0	
2–3	13	789	16.5	
3–4	12	776	15.5	
4–5	30	764	39.3	
5–6	46	734	62.7	
6–7	48	688	69.8	
7–8	69	640	107.8	
8–9	132	571	231.2	
9–10	187	439	426.0	
10–11	156	252	619.0	
11–12	90	96	937.5	
12–13	3	6	500.0	
13–14	3	3	1000	

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

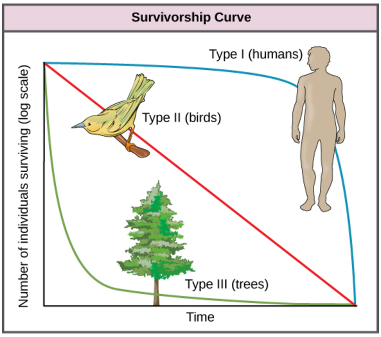


Figure 3. Survivorship curves show the distribution of individuals in a population according to age. Humans and most mammals have a Type I survivorship curve, because death primarily occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees have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

Attribution

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

Population Growth

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

Exponential Growth

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

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

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

Logistic Growth

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

Carrying Capacity and the Logistic Model

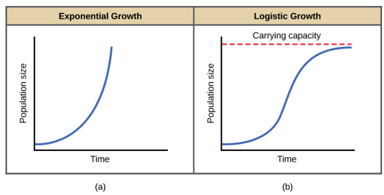


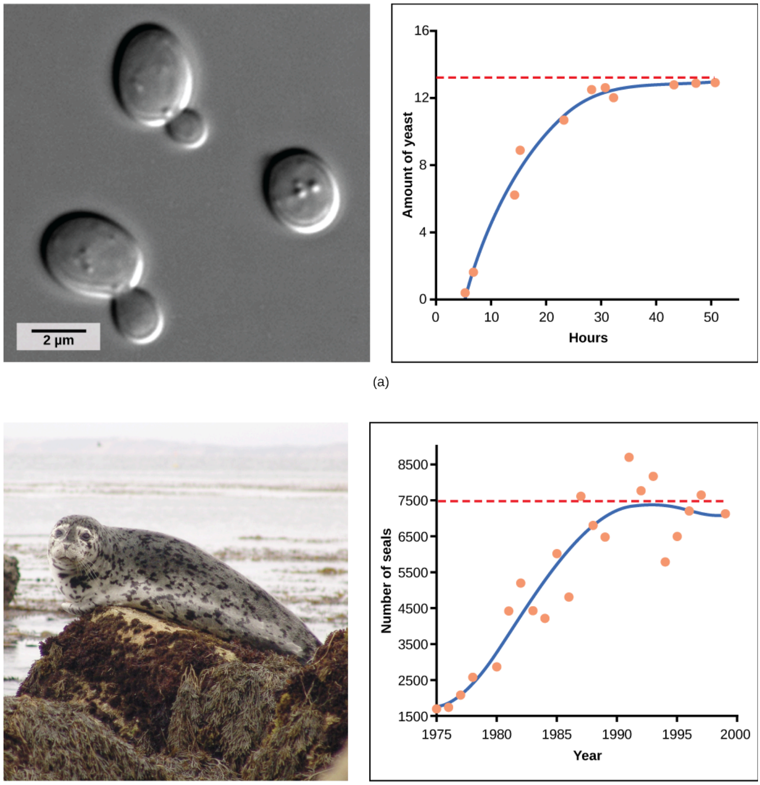
Figure 1. When resources are unlimited, populations exhibit (a) exponential growth, shown in a J-shaped curve. When resources are limited, populations exhibit (b) logistic growth. In logistic growth, population expansion decreases as resources become scarce, and it levels off when the carrying capacity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

In the real world, with its limited resources, exponential growth cannot continue indefinitely. Exponential growth may occur in environments where there are few individuals and plentiful resources, but when the number of individuals gets large enough, resources will be depleted and the growth rate will slow down. Eventually, the growth rate will plateau or level off (Figure 1). This population size, which is determined by the maximum population size that a particular environment can sustain, is called the **carrying capacity**, symbolized as *K*. In real populations, a growing population often overshoots its carrying capacity and the death rate increases beyond the birth rate causing the population size to decline back to the carrying capacity or below it. Most populations usually fluctuate around the carrying capacity in an undulating fashion rather than existing right at it.

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

Examples of Logistic Growth

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



(b)

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

Population Dynamics and Regulation

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

Why Did the Woolly Mammoth Go Extinct?

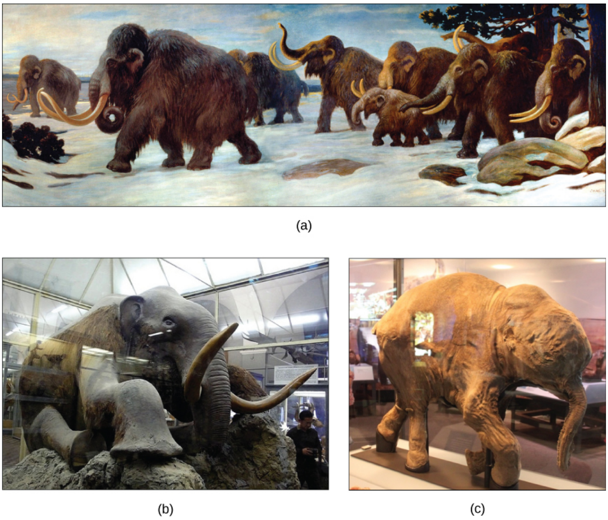


Figure 3. The three images include: (a) 1916 mural of a mammoth herd from the American Museum of Natural History, (b) the only stuffed mammoth in the world is in the Museum of Zoology located in St. Petersburg, Russia, and (c) a one-month-old baby mammoth, named Lyuba, discovered in Siberia in 2007.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

Most populations of woolly mammoths went extinct about 10,000 years ago, soon after paleontologists believe humans began to colonize North America and northern Eurasia (Figure 3). A mammoth population survived on Wrangel Island, in the East Siberian Sea, and was isolated from human contact until as recently as 1700 BC. We know a lot about these animals from carcasses found frozen in the ice of Siberia and other northern regions.

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

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

Demographic-Based Population Models

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

Attribution

Community Ecology

MATTHEW R. FISHER

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

Predation and Herbivory

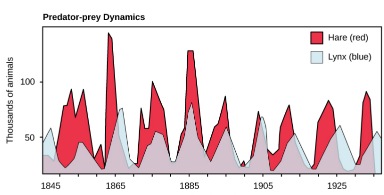


Figure 1. The cycling of snowshoe hare and lynx populations in Northern Ontario is an example of predator-prey dynamics.

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

Defense Mechanisms against Predation and Herbivory

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

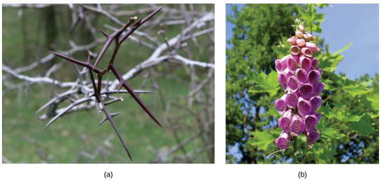


Figure 2. The (a) honey locust tree uses thorns, a mechanical defense, against herbivores, while the (b) foxglove uses a chemical defense: toxins produces by the plant can cause nausea, vomiting, hallucinations, convulsions, or death when consumed. (credit a: modification of work by Huw Williams; credit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

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

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

(a) (b)

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

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

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

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

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

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

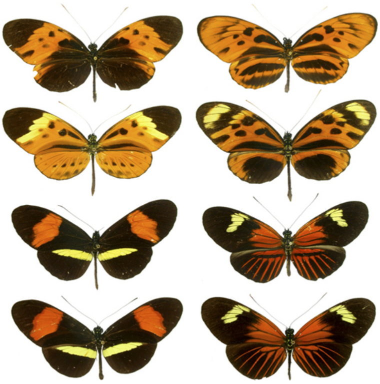


Figure 6. Several unpleasant-tasting Heliconius butterfly species share a similar color pattern with better-tasting varieties, an example of mimicry. (credit: Joron M, Papa R, Beltrán M, Chamberlain N, Mavárez J, et al.)

Link to Learning: Go to this website to view stunning examples of mimicry.

11. Soils

What is Soil?

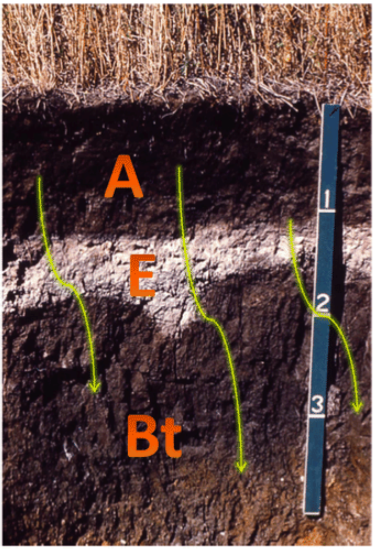


Figure 1. Soil Profile. Photograph shows a soil profile from South Dakota with A, E, and Bt horizons. The yellow arrows symbolize translocation of fine clays to the Bt horizon. The scale is in feet. Source: University of Idaho and modified by D. Grimley.

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

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

Importance of Soil

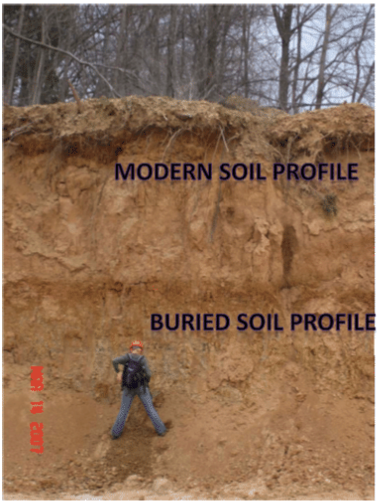


Figure 2. Modern versus Buried Soil Profiles. A buried soil profile, or paleosol (above geologist 's head), represents soil development during the last interglacial period. A modern soil profile (Alfisol) occurs near the land surface. Source: D. Grimley.

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

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

Soil Forming Factors

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

Climate

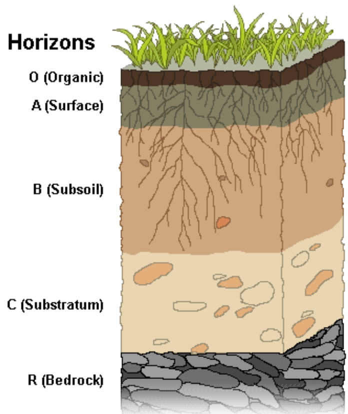


Figure 3. This images shows the different horizons, or layers, in soil. This work by Wilsonbiggs is licensed under CC BY-SA 4.0

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

Organisms

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

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

Relief (Topography and Drainage)

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

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

Parent Material

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

Time

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

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

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

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

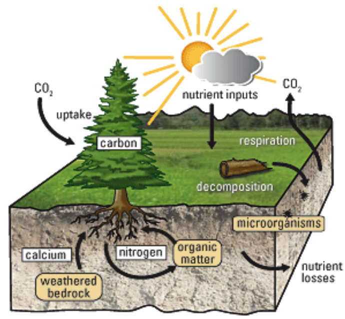


Figure 1. Soil-Plant Nutrient Cycle. This figure illustrates the uptake of nutrients by plants in the forest-soil ecosystem. Source: U.S. Geological Survey.

Nutrient Uptake by Plants

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

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

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

Attribution

This is where you can add appendices or other back matter.

Glossary

BILL FREEDMAN

accuracy: The degree to which a measurement or observation reflects the actual value. Compare with precision.

acid rain: The wet deposition only of acidifying substances from the atmosphere. See also acidifying deposition.

acid shock: An event of relatively acidic surface water that can occur in the springtime when the snowpack melts quickly but the ground is still frozen.

acid sulphate soil: Acidic soil conditions caused when certain wetlands are drained and sulphide compounds become oxidized.

acid-mine drainage: Acidic water and soil conditions that develop when sulphide minerals become exposed to the atmosphere, allowing them to be oxidized by Thiobacillus bacteria.

acid-neutralizing capacity: The quantitative ability of water to neutralize inputs of acid without becoming acidified. See also buffering capacity.

acidification: An increasing concentration of hydrogen ions (H^+) in soil or water.

acidifying deposition: Both the wet and dry deposition of acidifying substances from the atmosphere.

acute toxicity: Toxicity associated with short-term exposures to chemicals in concentrations high enough to cause biochemical or anatomical damages, even death. Compare with chronic toxicity.

aerobic: Refers to an environment in which oxygen (O_2) is readily available. Compare with anaerobic.

aesthetic pollution: Substantially a matter of cultural values, this commonly involves images that are displeasing to many (but not necessarily all) people.

afforestation: Establishment of a forest where one did not recently occur, as when trees are planted on agricultural land.

age-class structure: The proportions of individuals in various age classes of a population.

agricultural site capability: See site capability.

agroecosystem: An ecosystem used for the production of food.

agroforestry: The cultivation of trees in plantations, typically using relatively intensive management practices.

algal bloom: An event of high phytoplankton biomass.

ammonification: Oxidation of the organically bound nitrogen of dead biomass into ammonium (NH_4^+).

anaerobic: Refers to an environment in which oxygen (O_2) is not readily available. Compare with aerobic.

angiosperm: Flowering plants that have their ovules enclosed within a specialized membrane and their seeds within a seedcoat. Compare with gymnosperm.

anthropocentric world view: This considers humans as being more worthy than other species and uniquely disconnected from nature. The importance and worth of everything is considered in terms of the implications for human welfare. Compare with biocentric world view and ecocentric world view.

anthropogenic: Occurring as a result of a human influence.

applied ecology: The application of ecological principles to deal with economic and environmental problems.

aquaculture: The cultivation of fish and other aquatic species.

aquifer: Groundwater resources in some defined area.

artificial selection: The deliberate breeding of species to enhance traits that are viewed as desirable by humans.

artificial wetland: An engineered wetland, usually constructed to treat sewage or other organic wastes.

aspect: The direction in which a slope faces.

assimilation efficiency: In an animal, the percentage of the energy content of ingested food that is absorbed across the gut wall. In plants, the percentage of solar visible light that is fixed by photosynthesis. The term may also be used to refer to the percentage assimilation of ingested inorganic nutrients (such as nitrate or phosphate) by plants or animals, or of drugs by animals.

atmosphere: The gaseous envelope surrounding the Earth, held in place by gravity.

atmospheric inversion (temperature inversion): A relatively stable atmospheric condition in which cool air is trapped beneath a layer of warmer air.

atmospheric water: Water occurring in the atmosphere, in vapour, liquid, or solid forms.

atom bomb: An explosive device that is based on the uncontrolled "splitting" of certain fissile isotopes of uranium and/or plutonium.

autecology: The field within ecology that deals with the study of individuals and species. Compare with synecology.

autotroph: An organism that synthesizes its biochemical constituents using simple inorganic compounds and an external source of energy to drive the process. See also primary producer, photoautotroph, and chemoautotroph.

available concentration: The concentration of metals in an aqueous extract of soil, sediment, or rocks, simulating the amount available for organisms to take up from the environment. Compare with total concentration.

baby boom: A period of high fecundity during 1945–1965 that occurred because of social optimism after the Second World War.

background concentration: A presence or concentration of a substance that is not significantly influenced by either anthropogenic emissions or unusual natural exposures.

binomial: Two latinized words that are used to name a species.

bioaccumulation (bioconcentration): The occurrence of chemicals in much higher concentrations in organisms than in the ambient environment. Compare with food-web magnification.

biocentric world view: This considers all species (and individuals) as having equal intrinsic value. Humans are not considered more important or worthy than any other species. Compare with anthropocentric world view and ecocentric world view.

bioconcentration: See bioaccumulation.

biodegradation: The breakdown of organic molecules into simpler compounds through the metabolic actions of microorganisms.

biodiversity: The richness of biological variation, including genetic variability as well as species and community richness.

biodiversity crisis: The present era of high rates of extinction and endangerment of biodiversity.

biogeochemical prospecting: Prospecting for metal ores using observations of high metal concentrations in plants, soil, or surface rocks.

biological control: Pest-control methods that depend on biological interactions, such as diseases, predators, or herbivores.

biological oxygen demand (BOD): The capacity of organic matter and other substances in water to consume oxygen during decomposition.

biomagnification: See food-web magnification.

biomass energy: The chemical potential energy of plant biomass, which can be combusted to provide thermal energy.

biome: A geographically extensive ecosystem, occurring throughout the world wherever environmental conditions are suitable.

biophilia: An innate love of people for nature

bio-resource: A renewable resource that is biological in character.

biosphere: All life on Earth, plus their ecosystems and environments.

birth control: Methods used to control fertility and childbirth.

BOD: See biological oxygen demand.

bog: An infertile, acidic, unproductive wetland that develops in cool but wet climates. Compare with fen.

boreal coniferous forest: A northern forest dominated by coniferous trees, usually species of fir, larch, pine, or spruce. See also boreal forest.

boreal forest (taiga): An extensive biome occurring in environments with cold winters, short but warm growing seasons, and moist soils, and usually dominated by coniferous trees.

broad-spectrum pesticide: A pesticide that is toxic to other organisms as well as the pest.

broadcast spray: A pesticide treatment over a large area.

browse: Broad-leaved shrubs that are eaten by herbivores such as hares and deer.

bryophyte: Simple plants that do not have vascular tissues nor a cuticle on their foliage.

by-catch: Inadvertent harvesting of a non-target species.

buffering capacity: The ability of a solution to resist changes in pH as acid or base is added.

calorie: A standard unit of energy, defined as the amount of energy needed to raise the temperature of one gram of pure water from 15°C to 16°C. Compare with joule.

carbon credits: Actions that help reduce the atmospheric concentration of CO_2, such as fossil-fuel conservation and planting trees.

carbon credits: See carbon credits.

carnivore (secondary consumer): An animal that hunts and eats other animals.

carrying capacity: The abundance of a species that can be sustained without the habitat becoming degraded.

chaparral: A shrub-dominated ecosystem that occurs in south-temperate environments with winter rains and summer drought.

chemical weapons: Weapons that cause deaths or injuries through exposure to toxic chemicals.

chemoautotroph: Microorganisms that harness some of the potential energy of certain inorganic chemicals (e.g., sulphides) to drive their fixation of energy through chemosynthesis. Compare with photoautotroph.

chemosynthesis: Autotrophic productivity that utilizes energy released during the oxidation of certain inorganic chemicals (such as sulphides) to drive biosynthesis. Compare with photosynthesis.

chromosome: Subcellular unit composed of DNA and containing the genetic information of eukaryotic organisms.

chronic toxicity: Toxicity associated with exposure to small or moderate concentrations of chemicals, sometimes over a long period of time. The damages may be biochemical or anatomical, and may include the development of a lethal disease, such as cancer. Compare with acute toxicity.

clear-cutting: The harvesting of all economically useful trees from an area at the same time.

climate: The prevailing, long-term, meteorological conditions of a place or region, including temperature, precipitation, wind speed, and other factors. Compare with weather.

climate change: Long-term changes in air, soil, or water temperature; precipitation regimes; wind speed; or other climate-related factors.

coal: An organic-rich, solid fossil fuel mined from sedimentary geological formations.

coal washing: See fuel desulphurization.

coarse woody debris: Logs lying on the forest floor.

coevolution: This occurs when species interact in ways that affect their reciprocal survival, and so are subject to a regime of natural selection that reinforces their mutual evolutionary change.

collective properties: This term is used in reference to the summation of the parts of a system. See also emergent properties.

commensalism: A symbiosis in which one of the species benefits from the interaction, while the other is not affected in either a positive or negative way.

commercial energy production: The use of solid, liquid, and gaseous fuels, plus all electricity. Does not include the use of traditional fuels. See also total energy production and traditional fuels.

commercial extinction: Depletion of a natural resource to below the abundance at which it can be profitably harvested.

common-property resource: A resource shared by all of society, not owned by any particular person or interest.

community: In ecology, this refers to populations of various species that are co-occurring at the same time and place.

community-replacing disturbance: A disturbance that results in the catastrophic destruction of an original community, and its replacement by another one. Compare with microdisturbance.

compaction: A decrease in the pore space of soil (or increased bulk density) caused by the passage of heavy machinery.

compartment: A reservoir of mass in a nutrient or material cycle.

competition: A biological interaction occurring when the demand for an ecological resource exceeds its limited supply, causing organisms to interfere with each other.

competitor: A species that is dominant in a habitat in which disturbance is rare and environmental stresses are unimportant, so competition is the major influence on evolution and community organization.

compost: Partially decomposed, well-humified organic material

composting: The processing of discarded organic material by encouraging decomposition processes under warm, moist, oxygen-rich conditions. The product, known as compost, is a useful fertilizer and soil conditioner.

conservation: Wise use of natural resources. Conservation of nonrenewable resources involves recycling and other means of efficient use. Conservation of renewable resources includes these means, in addition to ensuring that harvesting does not exceed the rate of regeneration of the stock.

contamination: The presence of potentially damaging chemicals in the environment, but at concentrations less than those required to cause toxicity or other ecological damages. Compare with pollution.

control (control treatment): An experimental treatment that was not manipulated, and is intended for comparison with manipulated treatments.

conventional economics: Economics as it is commonly practised, which includes not accounting for costs associated with ecological damages and resource depletion. Compare with ecological economics.

conventional munitions: Explosive devices that are based on chemical reactions, such as cordite and dynamite.

convergence (evolutionary conversion): This occurs when unrelated species with similar niches and living in comparable environments are subjected to parallel regimes of natural selection, resulting in their evolution to be similar in morphology, physiology, and behaviour.

conversion: See ecological conversion.

core: Earth's massive interior, made up of hot molten metals.

Coriolis effect: An influence of Earth's west-to-east rotation, which makes winds in the Northern Hemisphere deflect to the right and those in the Southern Hemisphere to the left.

creationist: A person who rejects the theory of evolution in favour of a literal interpretation of Genesis, the first book of the Old Testament of the Bible. See also scientific creationist.

critical load: A threshold for pollutant inputs, below which it is thought ecological damages will not be caused.

crude oil: See petroleum.

crude oil washing (COW) method: A method of washing a tanker's oil-storage components with a spray of crude oil before the next cargo is loaded. This eliminates the use of wash-water and avoids an important cause of marine oil pollution.

crust: The outermost layer of Earth's sphere, overlying the lithosphere and composed mostly of crystalline rocks.

cultural eutrophication: Eutrophication caused by anthropogenic nutrient inputs, usually through sewage dumping or fertilizer runoff. See also eutrophication.

cultural evolution: Adaptive evolutionary change in human society, characterized by increasing sophistication in the methods, tools, and social organizations used to exploit the environment and other species. Compare with evolution.

cultural identity: A complex of self-identified characteristics and values that a group of people considers important in defining their distinct quality.

culture: The shared beliefs, values, and knowledge of a defined group of people.

cumulative environmental impacts: Environmental impacts that result from a proposed undertaking, in addition to those caused by any past, existing, and imminent developments and activities.

decay: The decomposition or oxidation of dead biomass, mostly through the actions of microorganisms.

decomposer: See detritivore.

deductive logic: Logic in which initial assumptions are made and conclusions are then drawn from those assumptions. Compare with inductive logic.

deep drainage: Soil water that has drained to below the lower limits of plant roots.

deforestation: A permanent conversion of forest into some other kind of ecosystem, such as agriculture or urbanized land use.

demographic transition: A change in human population parameters from a condition of high birth and death rates to one of low birth and death rates.

denitrification: The microbial reduction of nitrate (NO_3^-) into gaseous N_2O or N_2.

desert: A temperate or tropical biome characterized by prolonged drought, usually receiving less than 25 cm of precipitation per year.

desertification: The increasing aridity of drylands; an environmental change that can make agriculture difficult or impossible.

detritivore: A heterotroph that feeds on dead organic matter.

developed countries: Countries with a relatively well-organized economic infrastructure and a high average per-capita income. See also high-income countries and compare with less-developed countries.

development (economic development): An economic term that implies improving efficiency in the use of materials and energy in an economy, and progress toward a sustainable economic system. Compare with economic growth.

discipline: A specific area of study, such as mathematics or music.

disturbance: An episode of destruction of some part of a community or ecosystem.

DNA: The biochemical deoxyribonucleic acid, the main constituent of the chromosomes of eukaryotic organisms.

domestication: The genetic, anatomic, and physiological modification of crops and other species from their wild, progenitor species, through the selective breeding of preferred races (or cultivars).

dose-response relationship: The quantitative relationship between different doses of a chemical and a biological or ecological response.

doubling time: The time it takes for something to increase by a factor of two (as in population growth).

drift: Movement of applied pesticide off the intended site of deposition through atmospheric or aquatic transport.

dry deposition: Atmospheric inputs of chemicals occurring in intervals between rainfall or snowfall. Compare with wet deposition.

dumping: The long-term disposal of disused material, for example, by placing solid waste into a sanitary landfill, or by discarding liquid waste into a waterbody.

earthquake: A trembling or movement of the earth, caused by a sudden release of geological stresses at some place within the crust.

ecocentric world view: This incorporates the biocentric world view but also stresses the importance of interdependent ecological functions, such as productivity and nutrient cycling. In addition, the connections among species within ecosystems are considered to be invaluable. Compare with anthropocentric world view and biocentric world view.

ecofeminism: A philosophical and political movement that applies feminist ideas to environmental concerns.

ecological conversion: A long-term change in the character of the ecosystem at some place, as when a natural forest is converted into an agricultural land use.

ecological economics: A type of economics that involves a full accounting of costs associated with ecological damages and resource depletion. Compare with conventional economics.

ecological footprint: The area of ecoscape (i.e., landscape and seascape) required to supply a human population with the necessary food, materials, energy, waste disposal, and other crucial goods and services.

ecological integrity (ecosystem health): A notion related to environmental quality, but focusing on changes in natural populations and ecosystems, rather than effects on humans and their economy. See also environmental quality.

ecological justice: A worldview in which all species (i.e., not just humans) have a right to equitable access to the necessities of life and happiness. See also social justice.

ecological pyramid: A model of the trophic structure of an ecosystem, organized with plant productivity on the bottom, that of herbivores above, and carnivores above the herbivores.

ecological service: An ecological function that is useful to humans and to ecosystem stability and integrity, such as nutrient cycling, productivity, and control of erosion.

ecological stress: See stressors.

ecological sustainability: See ecologically sustainable development.

ecological values: Broader utilitarian values that are based on the needs of humans, but also on those of other species and natural ecosystems.

ecologically sustainable development: This considers the human need for resources within an ecological context, and includes the need to sustain all species and all components of Earth's life-support system. Compare with sustainable development.

ecologically sustainable economic system: An economic system that operates without a net consumption of natural resources, and without endangering biodiversity or other ecological values. Ultimately, ecologically sustainable economic systems are supported by the wise use of renewable resources.

ecologically sustainable economy: An economy in which ecological goods and services are utilized in ways that do not compromise their future availability and do not endanger the survival of species or natural ecosystems.

ecology: The study of the relationships between organisms and their environment.

economic development: See development.

economic growth: A term that refers to an economy that is increasing in size over time, usually due to increases in both population and per capita resource use. Compare with development.

ecoregion: See ecozone.

ecoscape: A general term for landscapes or seascapes.

ecosystem: A general term used to describe one or more communities that are interacting with their environment as a defined unit. Ecosystems range from small units occurring in microhabitats, to larger units such as landscapes and seascapes, and even the biosphere.

ecosystem approach: A holistic interpretation of the natural world that considers the web-like interconnections among the many components of ecosystems.

ecosystem health: See ecological integrity.

ecotone: A zone of transition between two distinct habitats.

ecotoxicology: Study of the directly poisonous effects of chemicals in ecosystems, plus indirect effects such as changes in habitat or food abundance caused by toxic exposures. Compare with toxicology and environmental toxicology.

ecotype: A population specifically adapted to coping with locally stressful conditions, such as soil with high metal concentrations.

ecozone: The largest biophysical zones in the national ecological classification of Canada.

electromagnetic energy: Energy associated with photons, comprising an electromagnetic spectrum divided into components, including ultraviolet, visible, and infrared.

emergent property: A used in reference to synergetic properties that are greater than the summation of the parts of a system. See also collective properties.

emissions trading: A system in which a company whose that has not exceeded its cap on emissions of a regulated substance, such as SO_2, can sell its "surplus" to another that is likely to exceed its cap.

endangered: In Canada, this specifically refers to indigenous species threatened with imminent extinction or extirpation over all or a significant portion of their Canadian range.

endemic: An ecological term used to describe species with a local geographic distribution.

energy: The capacity of a body or system to accomplish work, and existing as electromagnetic, kinetic, and potential energies.

energy budget: An analysis of the rates of input and output of energy to a system, plus transformations of energy among its states, including changes in stored quantities.

energy production: See total energy production.

entropy: A physical attribute related to the degree of randomness of the distributions of matter and energy.

environment (the): (1) Refers to influences on organisms and ecosystems, including both non-living (abiotic) and biological factors; (2) An indeterminate word for issues associated with the causes and consequences of environmental damage, or with the larger environmental crisis.

environmental citizenship: Actions taken by individuals and families to lessen their impacts on the environment.

environmental degradation: Refers to pollution, disturbance, resource depletion, lost biodiversity, and other kinds of environmental damage; usually refers to damage occurring accidentally or intentionally as a result of human activities (see also anthropogenic), but can also be caused by natural disasters or stressors.

environmental discrimination (environmental prejudice): Discrimination against any defined group that results in them suffering a disproportionate amount of degradation or pollution of their living or work environment. See also environmental racism.

environmental ecology: See applied ecology

environmental education: A way of fostering environmental literacy by incorporating environmental issues in educational curricula, both in specialized classes as well as across the curriculum, and also including the out-of-school public.

environmental ethics: These deal with the responsibilities of the present human generation to ensure continued access to adequate resources and livelihoods for future generations of people and other species.

environmental impact assessment (EIA): A process used to identify and evaluate the potential consequences of proposed actions or policies for environmental quality. See also socioeconomic impact assessment.

environmental indicators: Relatively simple measurements that are sensitive to changes in the intensity of stressors, and are considered to represent complex aspects of environmental quality.

environmental literacy: Refers to an objective understanding, by individuals and society-at-large, of the causes and consequences of environmental problems.

environmental monitoring: Repeated measurements of indicators related to the inorganic environment or to ecosystem structure and function.

environmental mutagen: A mutagenic influence that is encountered in the environment. See also mutagen.

environmental non-governmental organizations (ENGOs): Charities and other not-for-profit organizations that are working in the environmental field. See also non-governmental organizations.

environmental quality: A notion related to the amounts of toxic chemicals and other stressors in the environment, to the frequency and intensity of disturbances, and to their effects on humans, other species, ecosystems, and economies.

environmental racism: Discrimination against a group of people defined by racial attributes, which results in them suffering a disproportionate amount of degradation or pollution of their living or work environment. See also environmental discrimination.

environmental reporting: Communication of information about changes in environmental quality to interest groups and the general public.

environmental risk: A hazard or probability of suffering damage or misfortune because of exposure to some environmental circumstance.

environmental risk assessment: A quantitative evaluation of the risks associated with an environmental hazard.

environmental science: An interdisciplinary branch of science that investigates questions related to the human population, resources, and damages caused by pollution and disturbance.

environmental scientist: A scientist who is specialized in some aspect of environmental science.

environmental security: The protection of people and the public interest from environmental risks, particularly those associated with anthropogenic activities and accidents, but may also include natural dangers.

environmental stressor: See stressor.

environmental studies: An extremely interdisciplinary approach that examines the scientific, social, and cultural aspects of environmental issues.

environmental teratogen: A teratogenic influence that is encountered in the environment. See also teratogen.

environmental toxicology: The study of environmental factors influencing exposures of organisms to potentially toxic levels of chemicals. Compare with toxicology and ecotoxicology.

environmental values: Perceptions of the worth of environmental components, divided into two broad classes: utilitarian and intrinsic.

environmentalist: Anyone with a significant involvement with environmental issues, usually in an advocacy sense.

erosion: The physical removal of rocks and soil through the combined actions of flowing water, wind, ice, and gravity.

estuary: A coastal, semi-enclosed ecosystem that is open to the sea and has habitats transitional between marine and freshwater conditions.

ethics: The perception of right and wrong. The proper behaviour of people toward each other and toward other species and nature.

eukaryote: Organisms in which the cells have an organized, membrane-bound nucleus containing the genetic material. Compare with prokaryote.

eutrophic: Pertains to waters that are highly productive because they contain a rich supply of nutrients. Compare with oligotrophic and mesotrophic.

eutrophication: Increased primary productivity of an aquatic ecosystem, resulting from nutrient inputs.

evaporation: The change of state of water from a liquid or solid to a gas.

evapotranspiration: Evaporation of water from a landscape. See also transpiration.

evolution: Genetically based changes in populations of organisms, occurring over successive generations.

evolutionary ecology: The interpretation of ecological knowledge in terms of evolution, natural selection, and related themes.

experiment: A controlled test or investigation designed to provide evidence for, or preferably against, a hypothesis about the natural or physical world.

exposure: In ecotoxicology, this refers to the interaction of organisms with an environmental stressor at a particular place and time.

exposure assessment: An investigation of the means by which organisms may encounter a potentially toxic level of a chemical or other environmental stressor.

externality: A cost or benefit that is received, even though the affected party did not choose to incur it.

extant: A species that still exists. Compare with extinct.

extinct (extinction): A condition in which a species or other taxon no longer occurs anywhere on Earth.

extinction crisis: See biodiversity crisis.

extinction vortex: An accelerating spiral of endangerment and extinction caused by worsening environmental conditions.

extirpated (extirpation): A condition in which a species or other taxon no longer occurs in some place or region, but still survives elsewhere.

fact: An event or thing known to have happened, to exist, or to be true. See also hypothesis.

fen: A wetland that develops in cool and wet climates, but is less acidic and more productive than a bog because it has a better nutrient supply. Compare with bog.

first law of thermodynamics: A physical principle stating that energy can undergo transformations among its various states, but it is never created or destroyed; thus, the energy content of the universe remains constant. See also second law of thermodynamics.

First Nations: The Aboriginal people(s) originally living in some place. This term is often used in reference to the original inhabitants of the Americas, prior to the colonization of those regions by Europeans, and their modern descendants.

fission bomb: See atom bomb.

fission reaction: Nuclear reaction involving the splitting of heavier, radioactive atoms into lighter ones, with the release of large quantities of energy.

fitness: The proportional contribution of an individual to the progeny of its population.

flow-through system: A system with an input and an output of energy or mass, plus temporary storage of any difference.

flue-gas desulphurization: A process to remove SO_2 from the waste (flue) gases of a power plant or smelter, before they are discharged into the atmsophere.

flux: A movement of mass or energy between compartments of a material or energy cycle.

food chain: A hierarchical model of feeding relationships among species in an ecosystem.

food web: A complex model of feeding relationships, describing the connections among all food chains within an ecosystem.

food-web magnification (food-web accumulation, food-web concentration): The tendency for top predators in a food web to have the highest residues of certain chemicals, especially organochlorines. Compare with bioaccumulation.

forest floor: Litter and other organic debris lying on top of the mineral soil of a forest.

forestry: The harvesting of trees and management of post-harvest succession to foster the regeneration of another forest.

fossil fuel: Organic-rich geological materials, such as coal, petroleum, and natural gas.

frontier world view: This asserts that humans have a right to exploit nature by consuming natural resources in boundless quantities. See also sustainability world view and spaceship world view.

fuel desulphurization: A process that removes much of the sulphur content of coal before it is used as a fuel in a power plant.

fuel switching: The replacement of a high-sulphur fuel, such as coal, by an energy source that does not emit sulphur gases, such as hydroelectricity or nuclear power.

full-cost accounting system: An accounting system that considers all costs, including those of environmental damage.

fungicide: A pesticide used to protect crop plants and animals from fungi that cause diseases or other damages.

fusion bomb: See hydrogen bomb.

fusion reaction: Nuclear reaction involving the combining of light nuclei, such as those of hydrogen, to make heavier ones, with the release of large quantities of energy. Fusion reactions occur under conditions of intense temperature and pressure, such as within stars and in hydrogen bombs.

Gaia hypothesis: A notion that envisions Earth's species and ecosystems as a "superorganism" that attempts to optimize environmental conditions toward enhancing its own health and survival.

gaseous wastes: The gaseous products of combustion or industrial reactions.

gene: A region of a chromosome, containing a length of DNA that behaves as a particulate unit in inheritance and determines the development of a specific trait.

genocide: The mass killing of an identifiable group as an attempted extermination.

genotype: The genetic complement of an individual organism. See also phenotype.

geography: The study of the features of the surface of the Earth, including topography, landforms, soil, climate, and vegetation, as well as the intersections of these with the economic interests of humans.

geothermal energy: Heat in Earth's crust, which can sometimes be used to provide energy for heating or generation of electricity.

glaciation: An extensive environmental change associated with an extended period of global climatic cooling and characterized by advancing ice sheets.

glacier: A persistent sheet of ice, occurring in the Arctic and Antarctic and at high altitude on mountains.

greater protected area: A protected area plus its immediately surrounding area, co-managed to sustain populations of indigenous species and natural communities.

green manure: Living plant biomass that is grown and then incorporated into the soil by tillage.

green revolution: Intensive agricultural systems involving the cultivation of improved crop varieties in monoculture, and increased use of mechanization, fertilizers, and pesticides.

greenhouse effect: The physical process by which infrared-absorbing gases (such as CO_2) in Earth's atmosphere help to keep the planet warm.

greenhouses gases (GHGs): Atmospheric gases that efficiently absorb infrared radiation and then dissipate some of the thermal energy gain by re-radiation. Synonym: ** radiatively active gases.

gross domestic product (GDP): The total annual value of all goods and services produced domestically within a country. GDP is equivalent to gross national product minus net investment income from foreign countries. See also gross national product (GNP).

gross national product (GNP): The total annual value of all goods and services produced domestically by a country, including net foreign investment income. See also gross domestic product (GDP).

gross primary production (GPP): The fixation of energy by primary producers within an ecosystem. See also respiration, net primary production, and autotroph.

groundwater: Water stored underground in soil and rocks.

groundwater drainage: The drainage of water to storage places in the ground, occurring under the influence of gravity.

growth: Refers to an economy or economic sector that is increasing in size over time. Compare with development.

gymnosperm: Vascular plants such as conifers, which have naked ovules not enclosed within a specialized membrane, and seeds without a seedcoat. Compare with angiosperm.

habitat: The place or "home" where a plant or animal lives, including the specific environmental factors required for its survival.

harvesting effort: The amount of harvesting, which is a function of both the means (such as the kinds of fishing gear) and the intensity (the number of boats and the amount of time each spends fishing).

harvesting mortality: Anthropogenic mortality, especially that due to the harvesting of a bio-resource. Compare with natural mortality.

hazardous waste: Wastes that are flammable, explosive, toxic, or otherwise dangerous. See also toxic waste.

herbicide: A pesticide used to kill weeds. See also weed.

herbivore (or primary consumer): An animal that feeds on plants.

heterotroph: An organism that utilizes living or dead biomass as food.

hidden injury: A reduction in plant productivity caused by exposure to pollutants, but not accompanied by symptoms of acute tissue damages.

high-income countries: Countries with a relatively high average per-capita income. See also developed countries and compare with low-income countries.

hormone: A biochemical produced in an endocrine gland (and transported by the blood) that functions to regulate a metabolic process. Some chemicals in food may mimic the function of hormones produced naturally in the body.

hormonally active substance: A hormone or another chemical that has an effect on the regulation of biochemistry. See also hormone.

humidity: The actual concentration of water in the atmosphere, usually measured in mg/m^3. Compare with relative humidity.

humus: Amorphous, partially decomposed organic matter. An important and persistent type of soil organic matter, it is very important in soil tilth and fertility.

hydrocarbons: Molecules composed of hydrogen and carbon only.

hydroelectric energy: Electricity generated using the kinetic energy.

hydrogen bomb: A nuclear weapon that is based on the fusion of nuclei of deuterium and tritium, two isotopes of hydrogen.

hydrologic (water) cycle: The movement between, and storage of water in, various compartments of the hydrosphere. See also hydrosphere.

hydrosphere: The parts of the planet that contain water, including the oceans, atmosphere, on land, in surface waterbodies, underground, and in organisms.

hyperaccumulator: A species that bioaccumulates metals or other chemicals to extremely high concentrations in their tissues. See also bioaccumulation.

hypereutrophic: Extremely eutrophic waters; usually considered to be a degraded ecological condition. See also eutrophic.

hypersensitivity: An extreme sensitivity to exposure to some environmental factor, resulting in a biological response such as asthma, disease, or even death. It may be expressed at the species or individual level, and it involves responses at relatively low intensities of exposure that the great majority of species or individuals could tolerate.

hypothesis: A proposed explanation for the occurrence or causes of natural phenomena. Scientists formulate hypotheses as statements, and test them through experiments and other forms of research. See also fact.

igneous rock: Rock such as basalt and granite, formed by cooling of molten magma.

impoundment: An area of formerly terrestrial landscape that is flooded behind a dam.

incineration: The combustion of mixed solid wastes to reduce the amount of organic material present.

indicator: See environmental indicator.

indigenous culture: A human culture existing in a place or region prior to its invasion, or other significant influence, by a foreign culture.

individual organism: A genetically and physically discrete living entity.

inductive logic: Logic in which conclusions are objectively developed from the accumulating evidence of experience and the results of experiments. See also deductive logic.

inequitable: Not equitable or fair.

inherent value: See intrinsic value

inhumane: Reflecting a lack of pity or compassion; most commonly refers to the cruel treatment by humans of other animals.

insecticide: A pesticide used to kill insects that are considered pests. See also pesticide and pest.

instrumental value: See utilitarian value

integrated forest management: Forest management plans that accommodate the need to harvest timber from landscapes, while also sustaining other values, such as hunted wildlife, outdoor recreation, and biodiversity.

integrated pest management (IPM): The use of a variety of complementary tactics toward pest control, with the aim of having fewer environmental and health risks.

interdisciplinary: Encompassing a wide diversity of kinds of knowledge.

intrinsic population change: Population change due only to the balance of birth and death rates.

intrinsic value: Value that exists regardless of any direct or indirect value in terms of the needs or welfare of humans.

invasive alien: Refers to non-native species that survive in wild habitats and possibly aggressively out-compete native species or cause other kinds of ecological damage.

inversion: See atmospheric inversion.

invertebrate: Any animal that lacks an internal skeleton, and in particular a backbone.

joule: A standard unit of energy, defined as the energy needed to accelerate 1 kg of mass at 1 m/s2 for a distance of 1 metre. Compare with calorie.

K-selected: Refers to organisms that produce relatively small numbers of large offspring. A great deal of parental investment is made in each progeny, which helps to ensure their establishment and survival. Compare with r-selected.

keystone species: A dominant species in a community, usually a predator, with an influence on structure and function that is highly disproportionate to its biomass.

kinetic energy: Energy associated with motion, including mechanical and thermal types.

knowledge: Information and understanding about the natural world.

landscape: The spatial integration of ecological communities over a large terrestrial area.

landscape ecology: Study of the spatial characteristics and temporal dynamics of communities over large areas of land (landscapes) or water (seascapes).

laws of thermodynamics: Physical principles that govern all transformations of energy. See also first law of thermodynamics and second law of thermodynamics.

leaching: The movement of dissolved substances through the soil with percolating rainwater.

legacy munitions: See unexploded ordinance.

lentic ecosystem: A freshwater ecosystem characterized by nonflowing water, such as a pond or lake. Compare with lotic ecosystem.

less-developed countries: Countries with a relatively well-organized economic infrastructure and a high average per-capita income. See also high-income countries and compare with developed countries.

life form: A grouping of organisms on the basis of their common morphological and physiological characteristics, regardless of their evolutionary relatedness.

life index (production life): The known reserves of a resource divided by its current rate of production.

liming: Treatment of a waterbody or soil to reduce acidity, usually by adding calcium carbonate or calcium hydroxide.

limiting factor: An environmental factor that is the primary restriction on the productivity of autotrophs in an ecosystem. See also Principle of Limiting Factors.

liquid waste: Variable urban wastes that include sewage and discarded industrial and household fluids.

lithification: A geological process in which materials are aggregated, densified, and cemented into new sedimentary rocks.

lithosphere: An approximately 80-km thick region of rigid, relatively light rocks that surround Earth's plastic mantle.

load-on-top (LOT) method: A process used in ocean-going petroleum tankers to separate and contain most oily residues before ballast waters are discharged to the marine environment.

long-range transport of air pollutants: See LRTAP.

lotic ecosystem: A freshwater ecosystem characterized by flowing water, such as a stream or river. Compare with lentic ecosystem.

low-income counties: Countries with a relatively small average per-capita income. See also less-developed countries and compare with high-income countries.

LRTAP: The long-range transport of atmospheric pollutants.

macroclimate: Climatic conditions affecting an extensive area. Compare with microclimate.

macroevolution: The evolution of species or higher taxonomic groups, such as genera, families, or classes. Compare with microevolution.

management system: A variety of management practices used in a coordinated manner.

manipulative experiment: An experiment involving controlled alterations of factors hypothesized to influence phenomena, conducted to investigate whether predicted responses will occur, thereby uncovering causal relationships. See also experiment and natural experiment.

mantle: A less-dense region that encloses Earth's core, and composed of minerals in a hot, plastic state known as magma.

marsh: A productive wetland, typically dominated by species of monocotyledonous angiosperm plants that grow as tall as several metres above the water surface.

mass extinction: An event of synchronous extinction of many species, occurring over a relatively short period of time. May be caused by natural or anthropogenic forces.

maximum sustainable yield (MSY): The largest amount of harvesting that can occur without degrading the productivity of the stock.

mechanization: The use of specialized machinery to perform work, instead of the labour of people or animals.

megacity: A large city, sometimes defined as having a population greater than 8 million people.

mesosphere: The layer of the atmosphere extending beyond the stratosphere to about 75 km above the surface of the Earth. See also stratosphere.

mesotrophic: Pertains to aquatic ecosystems of moderate productivity, intermediate to eutrophic and oligotrophic waters. Compare with eutrophic and oligotrophic.

metal: Any relatively heavy element that in its pure state shares electrons among atoms, and has useful properties such as malleability, high conductivity of electricity and heat, and tensile strength.

metamorphic rock: Rock formed from igneous or sedimentary rocks that have changed in structure under the influences of geological heat and pressure.

meteorite: An extraterrestrial rock-like object; very rarely, one may intersect with Earth's orbit and impact the planet.

microclimate: Climatic conditions on a local scale. Compare with macroclimate.

microdisturbance: Local disruptions that affect small areas within an otherwise intact community. Compare with community-replacing disturbance.

microevolution: Relatively subtle evolutionary changes occurring within a population or species, sometimes within only a few generations, and at most leading to the evolution of races, varieties, or subspecies. Compare with macroevolution.

middle-income countries: Countries with a rapidly increasing average per-capita income. See also high-income and low-income countries and compare with developed countries and less-developed countries.

militarism: A belief of people or governments in the need to maintain a strong military capability to defend or promote national interests.

mitigation: An action that repairs or offsets environmental damages to some degree.

monoculture: The cultivation of only one species while attempting to exclude others from the agroecosystem.

montane forest: A conifer-dominated forest occurring below the alpine zone on mountains.

MSY: See maximum sustainable yield.

mutagen: A chemical or physical agent (e.g., ultraviolet radiation) that is capable of inducing genetic mutations.

mutualism (mutualistic symbiosis): A symbiosis in which both partners benefit.

natural: Refers to a non-anthropogenic context, i.e., one that is not influenced by humans and is self-organizing and dominated by native species; see also nature.

natural capital: See natural resource

natural experiment: An experiment conducted by observing variations of phenomena in nature, and then developing explanations for these through analysis of potential causal mechanisms. See also experiment and manipulative experiment.

natural gas: A gaseous, hydrocarbon-rich mixture mined from certain geological formations.

natural mortality: Mortality due to natural causes. Compare with harvesting mortality.

natural population change: A change in population that is due only to the difference in birth and death rates, and not to immigration or emigration.

natural resource: A source of material or energy that is extracted (harvested) from the environment.

natural selection: A mechanism of evolution, favouring individuals that, for genetically based reasons, are better adapted to coping with environmental opportunities and constraints. These more fit individuals have an improved probability of leaving descendants, ultimately leading to genetically based changes in populations, or evolution.

nature: Refers to the entire system of physical and biological existence and organization, uninfluenced by humans; see also natural.

net ecosystem productivity: The amount of ecosystem-level productivity that remains after respiration is subtracted from gross productivity.

net primary production (NPP): Primary production that remains as biomass after primary producers have accounted for their respiratory needs. See also respiration and gross primary production.

niche: The role of a species within its community.

NIMBY: An acronym for “not in my backyard”.

nitrification: The bacterial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-).

nitrogen fixation: The oxidation of nitrogen gas (N_2) to ammonia (NH_3) or nitric oxide (NO).

noise pollution: When the level of ambient sound becomes distracting to the normal activities of people. At a higher intensity it can cause hearing impairment.

non-governmental organizations (NGOs): Charities and other not- for-profit organizations. See also environmental non-governmental organizations.

non-renewable resource (non-renewable natural resource): A resource present on Earth in finite quantities, so as it is used, its future stocks are diminished. Examples are metals and fossil fuels. Compare with renewable resources.

non-target damage: Damage caused by a pesticide to non-target organisms. See also broad-spectrum pesticide and non-target organism.

non-target organism: Organisms that are not pests, but which may be affected by a pesticide treatment. See also broad-spectrum pesticide and non-target damage.

not in my backyard: See NIMBY.

nuclear fuel: Unstable isotopes of uranium (^{235}U) and plutonium (^{239}Pu) that decay through fission, releasing large amounts of energy that can be used to generate electricity.

nuclear winter: A period of prolonged climate cooling that might be caused by a nuclear war.

null hypothesis: A hypothesis that seeks to disprove a hypothesis.

nutrient: Any chemical required for the proper metabolism of organisms.

nutrient budget: A quantitative estimate of the rates of nutrient input and output for an ecosystem, as well as the quantities present and transferred within the system.

nutrient capital: The amount of nutrients present in a site in soil, living vegetation, and dead organic matter.

nutrient cycling: Transfers and chemical transformations of nutrients in ecosystems, including recycling through decomposition.

ocean: The largest hydrological compartment, accounting for about 97% of all water on Earth.

old-growth forest: A late-successional forest characterized by the presence of old trees, an uneven-aged population structure, and a complex physical structure.

oligotrophic: Pertains to aquatic ecosystems that are highly unproductive because of a sparse supply of nutrients. Compare with eutrophic and mesotrophic.

omnivore: An animal that feeds on both plant and animal materials.

organic agriculture: Systems by which crops are grown using natural methods of maintaining soil fertility, and pest-control methods that do not involve synthetic pesticides.

orographic precipitation: Precipitation associated with hilly or mountainous terrain that forces moisture-laden air to rise in altitude and become cooler, causing water vapour to condense into droplets that precipitate as rain or snow.

outer space: Regions beyond the atmosphere of Earth.

over-harvesting (over-exploitation): Unsustainable harvesting of a potentially renewable resource, leading to a decline of its stocks.

oxidizing smog: An event of air pollution rich in ozone, peroxy acetyl nitrate, and other oxidant gases.

paradigm: A pattern or model; a collection of assumptions, concepts, practices, and values that constitutes a way of viewing reality, especially for an intellectual community that shares them.

parameter: One or more constants that determine the form of a mathematical equation. In the linear equation $Y = aX + b$, a and b are parameters, and Y and X are variables. See also variable.

parasitism: A biological relationship involving one species obtaining nourishment from a host, usually without causing its death.

peace: The absence of war.

peace-keeping: An action that occurs after a hot conflict has stopped through a cease-fire agreement, but the conditions for a lasting peace are not yet in place so various means must be used to keep the antagonists apart. Compare with peace-making.

peace-making: The enforced resolution of an active or potential conflict, often by establishing a balanced power relationship among the parties while also imposing a process to achieve a negotiated settlement. Compare with peace-keeping.

persistence: The nature of chemicals, especially pesticides, to remain in the environment before eventually being degraded by microorganisms or physical agents such as sunlight and heat.

pest: Any organism judged to be significantly interfering with some human purpose.

pesticide: A substance used to poison pests. See also pest, fungicide, herbicide, and insecticide.

pesticide treadmill: The inherent reliance of modern agriculture and public-health programs on pesticides, often in increasing quantities, to deal with pest problems.

petroleum (crude oil): A fluid, hydrocarbon-rich mixture mined from certain geological formations.

phenotype: The expressed characteristics of an individual organism, due to genetic and environmental influences on the expression of its specific genetic information. See also genotype.

phenotypic plasticity: The variable expression of genetic information of an individual, depending on environmental influences during development.

photoautotroph: Plants and algae that use sunlight to drive their fixation of energy through photosynthesis. See also chemoautotroph and photosynthesis.

photochemical air pollutants: Ozone, peroxy acetyl nitrate, and other strongly oxidizing gases that form in the atmosphere through complex reactions involving sunlight, hydrocarbons, oxides of nitrogen, and other chemicals.

photosynthesis: Autotrophic productivity that utilizes visible electromagnetic energy (such as sunlight) to drive biosynthesis.

phytoplankton: Microscopic, photosynthetic bacteria and algae that live suspended in the water of lakes and oceans.

plantation: In forestry, these are tree-farms managed for high productivity of wood fibre.

poaching: The illegal harvesting of wild life (plants or animals).

point source: A location where large quantities of pollutants are emitted into the environment, such as a smokestack or sewer outfall.

political ecology: This integrates the concerns of ecology and political economy to consider the dynamic tensions between natural and anthropogenic change, and also the consideration of damage from both natural and anthropogenic perspectives; the latter includes the broad range of concerns from individual people to all of society.

pollution: The exposure of organisms to chemicals or energy in quantities that exceed their tolerance, causing toxicity or other ecological damages. Compare with contamination.

population: In ecology, this refers to individuals of the same species that occur together in time and space.

potential energy: The stored ability to perform work, capable of being transformed into electromagnetic or kinetic energies. Potential energy is associated with gravity, chemicals, compressed gases, electrical potential, magnetism, and the nuclear structure of matter.

potentially renewable natural resource: An alternate phrase for renewable natural resource, highlighting the fact that these can be overexploited, and thereby treated as if they were nonrenewable resources. See also renewable resource.

ppb (part per billion): A unit of concentration, equivalent to 1 microgram per kilogram (μg/kg), or in aqueous solution, 1 μg per litre (μg/L).

ppm (part per million): A unit of concentration, equivalent to 1 milligram per kilogram (mg/kg), or in aqueous solution, 1 mg per litre (mg/L).

prairie: Grassland ecosystems occurring in temperate regions.

precautionary principle: An approach to environmental management, adopted by many countries at the 1992 Earth Summit, which essentially states that scientific uncertainty is not a sufficient reason to postpone control measures when there is a threat of harm to human health or the environment.

precipitation: Deposition of water from the atmosphere as liquid rain, or as solid snow or hail.

precision: The degree of repeatability of a measurement or observation. Compare with accuracy.

prevailing wind: Wind that blows in a dominant direction.

primary consumer: A herbivore, or a heterotrophic organism that feeds on plants or algae.

primary pollutants: Chemicals that are emitted into the environment. Compare with secondary pollutants.

primary producer: An autotrophic organism. Autotrophs are the biological foundation of ecological productivity. See also primary production.

primary production: Productivity by autotrophic organisms, such as plants or algae. Often measured as biomass accumulated over a unit of time, or sometimes by the amount of carbon fixed.

primary sewage treatment: The initial stage of sewage treatment, usually involving the filtering of larger particles from the sewage wastes, settling of suspended solids, and sometimes chlorination to kill pathogens.

Principle of Limiting Factors: A theory stating that ecological productivity (and some other functions) is controlled by whichever environmental factor is present in least supply relative to the demand.

production: An ecological term related to the total yield of biomass from some area or volume of habitat.

production life: See life index.

productivity: An ecological term for production standardized per unit area and time.

prokaryote: Microorganisms without an organized nucleus containing their genetic material. Compare with eukaryote.

protected area (reserve): Parks, ecological reserves, and other tracts set aside from intense development to conserve their natural ecological values. See also greater protected area.

r-selected: Refers to organisms that produce relatively large numbers of small offspring. Little parental investment is made in each offspring, but having large numbers of progeny helps ensure that some will establish and survive. Compare with K-selected.

radiatively active gases (RAGs): Atmospheric gases that efficiently absorb infrared radiation and then dissipate some of the thermal energy gain by reradiation.

rapidly developing countries: Countries with a quickly growing economic infrastructure and a rapidly increasing average per-capita income. See also high-income and low-income countries and compare with developed countries and less-developed countries.

reclamation: Actions undertaken to establish a self-maintaining ecosystem on degraded land, as when a disused industrial site is converted into a permanent cover of vegetation, such as a pasture. Compare with restoration and remediation.

recycling: The processing of discarded materials into useful products.

relative humidity: The atmospheric concentration of water, expressed as a percentage of the saturation value for that temperature.

remediation: Specific actions undertaken to deal with particular problems of environmental quality, such as the liming of acidic lakes and rivers to decrease their ecological damage. Compare with restoration and reclamation.

renewable resource (renewable natural resource): These can regenerate after harvesting, and potentially can be exploited forever. Examples are fresh water, trees, agricultural plants and livestock, and hunted animals. Compare with nonrenewable resources.

replacement fertility rate: The fertility rate that results in the numbers of progeny replacing their parents, with no change in size of the equilibrium population.

replication: The biochemical process occurring prior to cellular division, by which information encoded in DNA is copied to produce additional DNA with the same information.

reserve: (1) Known quantities of resources that can be economically recovered from the environment. (2) An alternative word for a protected area. See protected area.

residence time: (1) The time required for the disappearance of an initial amount; (2) The length of time that a stressor or other environmental influence remains active.

residue: Lingering concentrations of pesticides and certain other chemicals in organisms and the environment.

resilience: The ability of a system to recover from disturbance.

resistance: The ability of a population or community to avoid displacement from some stage of ecological development as a result of disturbance or an intensification of environmental stress. Changes occur after thresholds of resistance to environmental stressors are exceeded.

resource recovery facility: See waste-to-energy facility.

respiration: Physiological processes needed to maintain organisms alive and healthy.

response: In ecotoxicology, this refers to biological or ecological changes caused by exposure to an environmental stressor.

restoration: Establishment of a self-maintaining facsimile of a natural ecosystem on degraded land, as when abandoned farmland is converted back to a native prairie or forest. Compare with reclamation and remediation.

restoration ecology: Activities undertaken by ecologists to repair ecological damage, such as establishing vegetation on degraded habitat, increasing the populations of endangered species, and decreasing the area of threatened ecosystems.

reuse: Finding another use for discarded materials, usually with relatively little modification.

risk: See environmental risks.

risk assessment: See environmental risk assessment.

RNA: The biochemical ribonucleic acid, which is important in translation of the genetic information of DNA into the synthesis of proteins. RNA also stores the genetic information of some viruses.

ruderal: Short-lived but highly fecund plants characteristic of frequently disturbed environments with abundant resources.

run-of-the-river: A hydroelectric development that directly harnesses the flow of a river to drive turbines, without creating a substantial impoundment for water storage.

salinization: The buildup of soluble salts in the soil surface, an important agricultural problem in drier regions.

sanitary landfill: A facility where municipal solid waste is dumped, compacted by heavy machines, and covered with a layer of clean dirt at the end of the day. Some have systems to contain and collect liquid effluent, known as leachate.

science: The systematic and quantitative study of the character and behaviour of the physical and biological world.

scientific creationist: A creationist who attempts to explain some of the discrepancies between his or her beliefs (which are based on a literal interpretation of Genesis) and scientific understanding of the origin and evolution of life. See also creationist.

scientific method: This begins with the identification of a question involving the structure or function of the natural world, usually using inductive logic. The question is interpreted in terms of a theory, and hypotheses are formulated and tested by experiments and observations of nature.

scrubbing: See flue-gas desulphurization.

seascape: A spatial integration of ecological communities over a large marine area.

second law of thermodynamics: A physical principle stating that transformations of energy can occur spontaneously only under conditions in which there is an increase in the entropy (or randomness) of the universe. See also first law of thermodynamics and entropy.

secondary consumer: A carnivore that feeds on primary consumers (or herbivores).

secondary pollutants: Pollutants that are not emitted, but form in the environment by chemical reactions involving emitted chemicals. Compare with primary pollutants.

secondary sewage treatment: Treatment applied to the effluent of primary sewage treatment, usually involving the use of a biological technology to aerobically decompose organic wastes in an engineered environment. The resulting sludge can be used as a soil conditioner, incinerated, or dumped into a landfill. See also primary sewage treatment.

sedimentary rock: Rock formed from precipitated minerals such as calcite, or from lithified particles eroded from other rocks such as sandstone, shale, and conglomerates.

sedimentation: A process by which mass eroded from elsewhere settles to the bottom of rivers, lakes, or an ocean.

seismic sea wave: See tsunami.

selection harvesting: Harvesting of only some trees from a stand, leaving others behind and the forest substantially intact.

sewage treatment: The use of physical filters, chemical treatment, and/or biological treatment to reduce pathogens, organic matter, and nutrients in waste waters containing sewage.

shifting cultivation: An agricultural system in which trees are felled, the woody debris burned, and the land used to grow mixed crops for several years.

significant figures: The number of digits used when reporting data from analyses or calculations.

silvicultural management: The application of practices that increase tree productivity in a managed forest, such as planting seedlings, thinning trees, or applying herbicides to reduce the abundance of weeds.

silviculture: The branch of forestry concerned with the care and tending of trees.

site capability (site quality): The potential of land to sustain the productivity of agricultural crops.

slash-and-burn: An agricultural system that results in a permanent conversion of a forest into crop production, involving cutting and burning the forest followed by continuous use of the land for crops.

slope: The angle of inclination of land, measured in degrees (0° implies a horizontal surface, while 90° is vertical).

SLOSS: An acronym, for single large or several small, in reference to choices in the design of protected areas.

sludge: A solid or semi-solid precipitate that settles from polluted water during treatment; sludge is produced during the treatment of sewage and also in pulp mills and some other industrial facilities. It may be disposed of in a landfill, but if organic, can be used as a beneficial soil amendment.

smog: An event of ground-level air pollution.

snag: A standing dead tree.

social justice: A worldview that calls for equality of consideration for all members of a society, regardless of colour, race, socio-economic class, gender, age, or sexual preference. See also ecological justice.

socio-cultural evolution: See cultural evolution.

socio-economic impact assessment: A process used to identify and evaluate the potential consequences of proposed actions or policies for sociological, economic, and related values. See also environmental impact assessment.

soil: A complex mixture of fragmented rock, organic matter, moisture, gases, and living organisms that covers almost all of Earth's terrestrial landscapes.

soil profile: The vertical stratification of soil on the basis of colour, texture, and chemical qualities.

solar energy: Electromagnetic energy radiated by the sun.

solar system: The sun, its nine orbiting planets, miscellaneous comets, meteors, and other local materials.

solid wastes: Extremely variable municipal wastes that include discarded food, garden discards, newspapers, bottles, cans, construction debris, old cars, and disused furniture.

spaceship Earth: An image of Earth as viewed from space, which illustrates the fact that, except for sunlight, resources needed by humans are present only on that planet.

spaceship world view: This focuses on sustaining only those resources needed by humans and their economy, and it assumes that humans can exert a great degree of control over natural processes and can pilot “spaceship Earth.” See also frontier world view and sustainability world view.

special concern: Refers to a species that is not currently threatened but is at risk of becoming so for various reasons.

species: An aggregation of individuals and populations that can potentially interbreed and produce fertile offspring, and is reproductively isolated from other such groups.

speciesism: Discrimination (by humans) against other species purely on the basis that they are not human, especially as manifested by cruelty to or exploitation of animals, or merely by a lack of consideration of their interests.

species richness: The number of species in some area or place.

state-of-the-environment reporting: A governmental, corporate, or NGO function that involves public reporting on environmental conditions.

strategic weapon: Large explosive-yield weapons that are designed to be delivered by a missile or airplane over a distance of thousands of kilometres. Compare with tactical weapon.

stratosphere: The upper atmosphere, extending above the. from 8-17 km to as high as about 50 km. See also troposphere.

stress-tolerator: Long-lived plants adapted to habitats that are marginal in terms of climate, moisture, or nutrient supply, but are infrequently disturbed and therefore stable, such as tundra and desert.

stressor: An environmental factor that constrains the development and productivity of organisms or ecosystems.

succession: A process of community- level recovery following disturbance.

surface flow: Water that moves over the surface of the ground.

surface water: Water that occurs in glaciers, lakes, ponds, rivers, streams, and other surface bodies of water.

sustainability world view: This acknowledges that humans must have access to vital resources, but it asserts that the exploitation of resources should be governed by appropriate ecological, aesthetic, and moral values, and should not deplete the necessary resources. See also frontier world view and spaceship world view.

sustainable development: Refers to progress toward an economic system that uses natural resources in ways that do not deplete their stocks or compromise their availability to future generations.

sustainable economic system (sustainable economy): An economic system that can be maintained over time without any net consumption of natural resources.

swamp: A forested wetland, flooded seasonally or permanently.

symbiosis: An intimate relationship between different species. See also mutualism.

synecology: The study of relationships among species within communities. Compare with autecology.

system: A group or combination of regularly interacting and interdependent elements, which form a collective entity, but one that is more than the sum of its constituents. See also ecosystem.

tactical weapon: Smaller, numerous weapons that are intended for use in a local battlefield, and are delivered by smaller missiles, artillery, aircraft, or torpedoes. Compare with strategic weapon.

taiga: See boreal forest.

tectonic force: Force associated with crustal movements and related geological processes that cause structural deformations of rocks and minerals.

temperate deciduous forest: A forest occurring in relatively moist, temperate climates with short and moderately cold winters and warm summers, and usually composed of a mixture of angiosperm tree species.

temperate grassland: Grass-dominated ecosystems occurring in temperate regions with an annual precipitation of 25–60 cm per year; sufficient to prevent desert from developing but insufficient to support forest.

temperate rainforest: A forest developing in a temperate climate in which winters are mild and precipitation is abundant year-round. Because wildfire is rare, old-growth forests may be common.

temperature inversion: See atmospheric inversion.

teratogen: A chemical or physical agent that induces a developmental abnormality (i.e., a birth defect) in an embryo or fetus.

tertiary sewage treatment: Treatment applied to the effluent of secondary sewage treatment, usually involving a system to remove phosphorus and/or nitrogen from waste waters. See also primary sewage treatment and secondary sewage treatment.

theory: A general term that refers to a set of scientific laws, rules, and explanations supported by a large body of experimental and observational evidence, all leading to robust, internally consistent conclusions.

thermal pollution: An increase in environmental temperature sufficient to result in ecological change.

thermosphere: The layer of the atmosphere extending beyond the mesosphere to 450 km or more above the surface of the Earth. See also mesosphere.

threatened: In Canada, this refers to any indigenous taxa likely to become endangered (in Canada) if factors affecting their vulnerability are not reversed.

tidal energy: Energy that develops in oceanic surface waters because of the gravitational attraction between Earth and the Moon, and can potentially be used to generate electricity.

tilth: The physical structure of soil, closely associated with the concentration of humified organic matter. Tilth is important in water- and nutrient-holding capacity of soil, and is generally beneficial to plant growth.

tolerance: In ecotoxicology, this refers to a genetically based ability of organisms or species to not suffer toxicity when exposed to chemicals or other stressors.

total concentration: The concentrations of metals in soil, sediment, rocks, or water, as determined after dissolving samples in a strongly acidic solution. Compare with available concentration.

total energy production: The use of commercial energy plus traditional fuels in an economy. See also traditional fuels.

total-war economy: An economy that is wholly dedicated to supporting a war effort.

toxic waste: Waste that is poisonous to humans, animals, or plants. See also hazardous waste.

toxicology: The science of the study of poisons, including their chemical nature and their effects on the physiology of organisms. Compare with environmental toxicology and ecotoxicology.

traditional fuels: The non-commercial use of wood, charcoal, animal dung, and other biomass fuels for subsistence purposes, primarily for cooking food and heating homes. See also total energy production and commercial energy production.

transcription: A biochemical process by which the information of double-stranded DNA is encoded on complementary single strands of RNA, which are used to synthesize specific proteins.

translation: A biochemical process occurring on organelles known as ribosomes, in which information encoded in messenger RNA is used to synthesize particular proteins.

transpiration: The evaporation of water from plants. Compare with evapotranspiration.

trophic structure: The organization of productivity in an ecosystem, including the roles of autotrophs, herbivores, carnivores, and detritivores.

troposphere: The lower atmosphere, extending to 8–17 km.

tsunami: A fast-moving, sea-wave caused by an undersea earthquakes, which if large can cause enormous destruction of low-lying coastal places.

tundra: A treeless biome occurring in environments with long, cold winters and short, cool growing seasons.

unexploded ordinance (UXOs): Explosives that remain in place after a conflict has ended.

urban agglomeration: See megacity

urban forest: Urban areas having a substantial density and biomass of trees, although often most are non-native species.

urban planning: An active process of designing better ways of organizing the structure and function of cities, including an orderly siting of land uses and activities.

urbanization: The development of cities and towns on formerly agricultural or natural lands.

utilitarian value: The usefulness of a thing or function to humans.

value added: The increased value of something as a result of manufacturing or some other improvement.

valued ecosystem components (VECs): In environmental impact assessment, these are components of ecosystems perceived to be important to society as economically important resources, as rare or endangered species or communities, or for their cultural or aesthetic significance.

variable: A changeable factor believed to influence a natural phenomenon of interest or that can be manipulated during an experiment.

vascular plant: Relatively complex plants with specialized, tube-like vascular tissues in their stems for conducting water and nutrients.

VECs: See valued ecosystem components.

vector: Species of insects and ticks that transmit pathogens from alternate hosts to people or animals.

vertebrate: Animals with an internal skeleton, and in particular a backbone.

virgin field: In epidemiology, this is a population that is hypersensitive to one or more infectious diseases to which it has not been previously exposed.

volatile organic compounds: Organic compounds that evaporate to the atmosphere at typical environmental temperatures, so they are present in gaseous or vapour forms.

volcano: An opening in Earth's crust from which magmic materials, such as lava, rock fragments, and gases, are ejected into the atmosphere or oceanic waters.

war: A period of organized deadly conflict between human societies, countries, or another defined group.

waste: Any discarded materials. See also hazardous waste and toxic waste.

waste management: The handling of discarded materials using various methods. See also dumping, incineration, recycling, composting, reuse, and waste reduction.

waste prevention: See waste reduction.

waste reduction: Practices intended to reduce the amount of waste that must be disposed of. Also known as waste prevention.

waste-to-energy facility: An incinerator that burns organic waste and uses the heat generated to produce commercial energy.

water cycle: See hydrologic cycle.

watershed: An area of land from which surface water and groundwater flow into a stream, river, or lake.

wave energy: The kinetic energy of oceanic waves, which can be harnessed using specially designed buoys to generate electricity.

weather: The short-term, day-to-day or instantaneous meteorological conditions at a place or region. Compare with climate.

weathering: Physical and chemical processes by which rocks and minerals are broken down by such environmental agents as rain, wind, temperature changes, and biological influences.

weed: An unwanted plant that interferes with some human purpose.

wet deposition: Atmospheric inputs of chemicals with rain and snow. Compare with dry deposition.

wetland: An ecosystem that develops in wet places and is intermediate between aquatic and terrestrial ecosystems. See also bog, fen, marsh, and swamp.

whole-lake experiment: The experimental manipulation of one or more environmental factors in an entire lake.

wind: An air mass moving in Earth's atmosphere.

wind energy: The kinetic energy of moving air masses, which can be tapped and utilized in various ways, including the generation of electricity.

work: In physics, work is defined as the result of a force being applied over a distance.

working hypothesis: A hypothesis being tested in a scientific experiment or another kind of research. See also hypothesis and null hypothesis.

zero population growth (ZPG): When the birth rate plus immigration equal the death rate plus emigration.

zooplankton: Tiny animals that occur in the water column of lakes and oceans

Glossary

BILL FREEDMAN

accuracy: The degree to which a measurement or observation reflects the actual value. Compare with precision.

acid rain: The wet deposition only of acidifying substances from the atmosphere. See also acidifying deposition.

acid shock: An event of relatively acidic surface water that can occur in the springtime when the snowpack melts quickly but the ground is still frozen.

acid sulphate soil: Acidic soil conditions caused when certain wetlands are drained and sulphide compounds become oxidized.

acid-mine drainage: Acidic water and soil conditions that develop when sulphide minerals become exposed to the atmosphere, allowing them to be oxidized by Thiobacillus bacteria.

acid-neutralizing capacity: The quantitative ability of water to neutralize inputs of acid without becoming acidified. See also buffering capacity.

acidification: An increasing concentration of hydrogen ions (H^+) in soil or water.

acidifying deposition: Both the wet and dry deposition of acidifying substances from the atmosphere.

acute toxicity: Toxicity associated with short-term exposures to chemicals in concentrations high enough to cause biochemical or anatomical damages, even death. Compare with chronic toxicity.

aerobic: Refers to an environment in which oxygen (O_2) is readily available. Compare with anaerobic.

aesthetic pollution: Substantially a matter of cultural values, this commonly involves images that are displeasing to many (but not necessarily all) people.

afforestation: Establishment of a forest where one did not recently occur, as when trees are planted on agricultural land.

age-class structure: The proportions of individuals in various age classes of a population.

agricultural site capability: See site capability.

agroecosystem: An ecosystem used for the production of food.

agroforestry: The cultivation of trees in plantations, typically using relatively intensive management practices.

algal bloom: An event of high phytoplankton biomass.

ammonification: Oxidation of the organically bound nitrogen of dead biomass into ammonium (NH_4^+).

anaerobic: Refers to an environment in which oxygen (O_2) is not readily available. Compare with aerobic.

angiosperm: Flowering plants that have their ovules enclosed within a specialized membrane and their seeds within a seedcoat. Compare with gymnosperm.

anthropocentric world view: This considers humans as being more worthy than other species and uniquely disconnected from nature. The importance and worth of everything is considered in terms of the implications for human welfare. Compare with biocentric world view and ecocentric world view.

anthropogenic: Occurring as a result of a human influence.

applied ecology: The application of ecological principles to deal with economic and environmental problems.

aquaculture: The cultivation of fish and other aquatic species.

aquifer: Groundwater resources in some defined area.

artificial selection: The deliberate breeding of species to enhance traits that are viewed as desirable by humans.

artificial wetland: An engineered wetland, usually constructed to treat sewage or other organic wastes.

aspect: The direction in which a slope faces.

assimilation efficiency: In an animal, the percentage of the energy content of ingested food that is absorbed across the gut wall. In plants, the percentage of solar visible light that is fixed by photosynthesis. The term may also be used to refer to the percentage assimilation of ingested inorganic nutrients (such as nitrate or phosphate) by plants or animals, or of drugs by animals.

atmosphere: The gaseous envelope surrounding the Earth, held in place by gravity.

atmospheric inversion (temperature inversion): A relatively stable atmospheric condition in which cool air is trapped beneath a layer of warmer air.

atmospheric water: Water occurring in the atmosphere, in vapour, liquid, or solid forms.

atom bomb: An explosive device that is based on the uncontrolled "splitting" of certain fissile isotopes of uranium and/or plutonium.

autecology: The field within ecology that deals with the study of individuals and species. Compare with synecology.

autotroph: An organism that synthesizes its biochemical constituents using simple inorganic compounds and an external source of energy to drive the process. See also primary producer, photoautotroph, and chemoautotroph.

available concentration: The concentration of metals in an aqueous extract of soil, sediment, or rocks, simulating the amount available for organisms to take up from the environment. Compare with total concentration.

baby boom: A period of high fecundity during 1945–1965 that occurred because of social optimism after the Second World War.

background concentration: A presence or concentration of a substance that is not significantly influenced by either anthropogenic emissions or unusual natural exposures.

binomial: Two latinized words that are used to name a species.

bioaccumulation (bioconcentration): The occurrence of chemicals in much higher concentrations in organisms than in the ambient environment. Compare with food-web magnification.

biocentric world view: This considers all species (and individuals) as having equal intrinsic value. Humans are not considered more important or worthy than any other species. Compare with anthropocentric world view and ecocentric world view.

bioconcentration: See bioaccumulation.

biodegradation: The breakdown of organic molecules into simpler compounds through the metabolic actions of microorganisms.

biodiversity: The richness of biological variation, including genetic variability as well as species and community richness.

biodiversity crisis: The present era of high rates of extinction and endangerment of biodiversity.

biogeochemical prospecting: Prospecting for metal ores using observations of high metal concentrations in plants, soil, or surface rocks.

biological control: Pest-control methods that depend on biological interactions, such as diseases, predators, or herbivores.

biological oxygen demand (BOD): The capacity of organic matter and other substances in water to consume oxygen during decomposition.

biomagnification: See food-web magnification.

biomass energy: The chemical potential energy of plant biomass, which can be combusted to provide thermal energy.

biome: A geographically extensive ecosystem, occurring throughout the world wherever environmental conditions are suitable.

biophilia: An innate love of people for nature

bio-resource: A renewable resource that is biological in character.

biosphere: All life on Earth, plus their ecosystems and environments.

birth control: Methods used to control fertility and childbirth.

BOD: See biological oxygen demand.

bog: An infertile, acidic, unproductive wetland that develops in cool but wet climates. Compare with fen.

boreal coniferous forest: A northern forest dominated by coniferous trees, usually species of fir, larch, pine, or spruce. See also boreal forest.

boreal forest (taiga): An extensive biome occurring in environments with cold winters, short but warm growing seasons, and moist soils, and usually dominated by coniferous trees.

broad-spectrum pesticide: A pesticide that is toxic to other organisms as well as the pest.

broadcast spray: A pesticide treatment over a large area.

browse: Broad-leaved shrubs that are eaten by herbivores such as hares and deer.

bryophyte: Simple plants that do not have vascular tissues nor a cuticle on their foliage.

by-catch: Inadvertent harvesting of a non-target species.

buffering capacity: The ability of a solution to resist changes in pH as acid or base is added.

calorie: A standard unit of energy, defined as the amount of energy needed to raise the temperature of one gram of pure water from 15°C to 16°C. Compare with joule.

carbon credits: Actions that help reduce the atmospheric concentration of CO_2, such as fossil-fuel conservation and planting trees.

carbon credits: See carbon credits.

carnivore (secondary consumer): An animal that hunts and eats other animals.

carrying capacity: The abundance of a species that can be sustained without the habitat becoming degraded.

chaparral: A shrub-dominated ecosystem that occurs in south-temperate environments with winter rains and summer drought.

chemical weapons: Weapons that cause deaths or injuries through exposure to toxic chemicals.

chemoautotroph: Microorganisms that harness some of the potential energy of certain inorganic chemicals (e.g., sulphides) to drive their fixation of energy through chemosynthesis. Compare with photoautotroph.

chemosynthesis: Autotrophic productivity that utilizes energy released during the oxidation of certain inorganic chemicals (such as sulphides) to drive biosynthesis. Compare with photosynthesis.

chromosome: Subcellular unit composed of DNA and containing the genetic information of eukaryotic organisms.

chronic toxicity: Toxicity associated with exposure to small or moderate concentrations of chemicals, sometimes over a long period of time. The damages may be biochemical or anatomical, and may include the development of a lethal disease, such as cancer. Compare with acute toxicity.

clear-cutting: The harvesting of all economically useful trees from an area at the same time.

climate: The prevailing, long-term, meteorological conditions of a place or region, including temperature, precipitation, wind speed, and other factors. Compare with weather.

climate change: Long-term changes in air, soil, or water temperature; precipitation regimes; wind speed; or other climate-related factors.

coal: An organic-rich, solid fossil fuel mined from sedimentary geological formations.

coal washing: See fuel desulphurization.

coarse woody debris: Logs lying on the forest floor.

coevolution: This occurs when species interact in ways that affect their reciprocal survival, and so are subject to a regime of natural selection that reinforces their mutual evolutionary change.

collective properties: This term is used in reference to the summation of the parts of a system. See also emergent properties.

commensalism: A symbiosis in which one of the species benefits from the interaction, while the other is not affected in either a positive or negative way.

commercial energy production: The use of solid, liquid, and gaseous fuels, plus all electricity. Does not include the use of traditional fuels. See also total energy production and traditional fuels.

commercial extinction: Depletion of a natural resource to below the abundance at which it can be profitably harvested.

common-property resource: A resource shared by all of society, not owned by any particular person or interest.

community: In ecology, this refers to populations of various species that are co-occurring at the same time and place.

community-replacing disturbance: A disturbance that results in the catastrophic destruction of an original community, and its replacement by another one. Compare with microdisturbance.

compaction: A decrease in the pore space of soil (or increased bulk density) caused by the passage of heavy machinery.

compartment: A reservoir of mass in a nutrient or material cycle.

competition: A biological interaction occurring when the demand for an ecological resource exceeds its limited supply, causing organisms to interfere with each other.

competitor: A species that is dominant in a habitat in which disturbance is rare and environmental stresses are unimportant, so competition is the major influence on evolution and community organization.

compost: Partially decomposed, well-humified organic material

composting: The processing of discarded organic material by encouraging decomposition processes under warm, moist, oxygen-rich conditions. The product, known as compost, is a useful fertilizer and soil conditioner.

conservation: Wise use of natural resources. Conservation of nonrenewable resources involves recycling and other means of efficient use. Conservation of renewable resources includes these means, in addition to ensuring that harvesting does not exceed the rate of regeneration of the stock.

contamination: The presence of potentially damaging chemicals in the environment, but at concentrations less than those required to cause toxicity or other ecological damages. Compare with pollution.

control (control treatment): An experimental treatment that was not manipulated, and is intended for comparison with manipulated treatments.

conventional economics: Economics as it is commonly practised, which includes not accounting for costs associated with ecological damages and resource depletion. Compare with ecological economics.

conventional munitions: Explosive devices that are based on chemical reactions, such as cordite and dynamite.

convergence (evolutionary conversion): This occurs when unrelated species with similar niches and living in comparable environments are subjected to parallel regimes of natural selection, resulting in their evolution to be similar in morphology, physiology, and behaviour.

conversion: See ecological conversion.

core: Earth's massive interior, made up of hot molten metals.

Coriolis effect: An influence of Earth's west-to-east rotation, which makes winds in the Northern Hemisphere deflect to the right and those in the Southern Hemisphere to the left.

creationist: A person who rejects the theory of evolution in favour of a literal interpretation of Genesis, the first book of the Old Testament of the Bible. See also scientific creationist.

critical load: A threshold for pollutant inputs, below which it is thought ecological damages will not be caused.

crude oil: See petroleum.

crude oil washing (COW) method: A method of washing a tanker's oil-storage components with a spray of crude oil before the next cargo is loaded. This eliminates the use of wash-water and avoids an important cause of marine oil pollution.

crust: The outermost layer of Earth's sphere, overlying the lithosphere and composed mostly of crystalline rocks.

cultural eutrophication: Eutrophication caused by anthropogenic nutrient inputs, usually through sewage dumping or fertilizer runoff. See also eutrophication.

cultural evolution: Adaptive evolutionary change in human society, characterized by increasing sophistication in the methods, tools, and social organizations used to exploit the environment and other species. Compare with evolution.

cultural identity: A complex of self-identified characteristics and values that a group of people considers important in defining their distinct quality.

culture: The shared beliefs, values, and knowledge of a defined group of people.

cumulative environmental impacts: Environmental impacts that result from a proposed undertaking, in addition to those caused by any past, existing, and imminent developments and activities.

decay: The decomposition or oxidation of dead biomass, mostly through the actions of microorganisms.

decomposer: See detritivore.

deductive logic: Logic in which initial assumptions are made and conclusions are then drawn from those assumptions. Compare with inductive logic.

deep drainage: Soil water that has drained to below the lower limits of plant roots.

deforestation: A permanent conversion of forest into some other kind of ecosystem, such as agriculture or urbanized land use.

demographic transition: A change in human population parameters from a condition of high birth and death rates to one of low birth and death rates.

denitrification: The microbial reduction of nitrate (NO_3-) into gaseous N_2O or N_2.

desert: A temperate or tropical biome characterized by prolonged drought, usually receiving less than 25 cm of precipitation per year.

desertification: The increasing aridity of drylands; an environmental change that can make agriculture difficult or impossible.

detritivore: A heterotroph that feeds on dead organic matter.

developed countries: Countries with a relatively well-organized economic infrastructure and a high average per-capita income. See also high-income countries and compare with less-developed countries.

development (economic development): An economic term that implies improving efficiency in the use of materials and energy in an economy, and progress toward a sustainable economic system. Compare with economic growth.

discipline: A specific area of study, such as mathematics or music.

disturbance: An episode of destruction of some part of a community or ecosystem.

DNA: The biochemical deoxyribonucleic acid, the main constituent of the chromosomes of eukaryotic organisms.

domestication: The genetic, anatomic, and physiological modification of crops and other species from their wild, progenitor species, through the selective breeding of preferred races (or cultivars).

dose-response relationship: The quantitative relationship between different doses of a chemical and a biological or ecological response.

doubling time: The time it takes for something to increase by a factor of two (as in population growth).

drift: Movement of applied pesticide off the intended site of deposition through atmospheric or aquatic transport.

dry deposition: Atmospheric inputs of chemicals occurring in intervals between rainfall or snowfall. Compare with wet deposition.

dumping: The long-term disposal of disused material, for example, by placing solid waste into a sanitary landfill, or by discarding liquid waste into a waterbody.

earthquake: A trembling or movement of the earth, caused by a sudden release of geological stresses at some place within the crust.

ecocentric world view: This incorporates the biocentric world view but also stresses the importance of interdependent ecological functions, such as productivity and nutrient cycling. In addition, the connections among species within ecosystems are considered to be invaluable. Compare with anthropocentric world view and biocentric world view.

ecofeminism: A philosophical and political movement that applies feminist ideas to environmental concerns.

ecological conversion: A long-term change in the character of the ecosystem at some place, as when a natural forest is converted into an agricultural land use.

ecological economics: A type of economics that involves a full accounting of costs associated with ecological damages and resource depletion. Compare with conventional economics.

ecological footprint: The area of ecoscape (i.e., landscape and seascape) required to supply a human population with the necessary food, materials, energy, waste disposal, and other crucial goods and services.

ecological integrity (ecosystem health): A notion related to environmental quality, but focusing on changes in natural populations and ecosystems, rather than effects on humans and their economy. See also environmental quality.

ecological justice: A worldview in which all species (i.e., not just humans) have a right to equitable access to the necessities of life and happiness. See also social justice.

ecological pyramid: A model of the trophic structure of an ecosystem, organized with plant productivity on the bottom, that of herbivores above, and carnivores above the herbivores.

ecological service: An ecological function that is useful to humans and to ecosystem stability and integrity, such as nutrient cycling, productivity, and control of erosion.

ecological stress: See stressors.

ecological sustainability: See ecologically sustainable development.

ecological values: Broader utilitarian values that are based on the needs of humans, but also on those of other species and natural ecosystems.

ecologically sustainable development: This considers the human need for resources within an ecological context, and includes the need to sustain all species and all components of Earth's life-support system. Compare with sustainable development.

ecologically sustainable economic system: An economic system that operates without a net consumption of natural resources, and without endangering biodiversity or other ecological values. Ultimately, ecologically sustainable economic systems are supported by the wise use of renewable resources.

ecologically sustainable economy: An economy in which ecological goods and services are utilized in ways that do not compromise their future availability and do not endanger the survival of species or natural ecosystems.

ecology: The study of the relationships between organisms and their environment.

economic development: See development.

economic growth: A term that refers to an economy that is increasing in size over time, usually due to increases in both population and per capita resource use. Compare with development.

ecoregion: See ecozone.

ecoscape: A general term for landscapes or seascapes.

ecosystem: A general term used to describe one or more communities that are interacting with their environment as a defined unit. Ecosystems range from small units occurring in microhabitats, to larger units such as landscapes and seascapes, and even the biosphere.

ecosystem approach: A holistic interpretation of the natural world that considers the web-like interconnections among the many components of ecosystems.

ecosystem health: See ecological integrity.

ecotone: A zone of transition between two distinct habitats.

ecotoxicology: Study of the directly poisonous effects of chemicals in ecosystems, plus indirect effects such as changes in habitat or food abundance caused by toxic exposures. Compare with toxicology and environmental toxicology.

ecotype: A population specifically adapted to coping with locally stressful conditions, such as soil with high metal concentrations.

ecozone: The largest biophysical zones in the national ecological classification of Canada.

electromagnetic energy: Energy associated with photons, comprising an electromagnetic spectrum divided into components, including ultraviolet, visible, and infrared.

emergent property: A used in reference to synergetic properties that are greater than the summation of the parts of a system. See also collective properties.

emissions trading: A system in which a company whose that has not exceeded its cap on emissions of a regulated substance, such as SO_2, can sell its "surplus" to another that is likely to exceed its cap.

endangered: In Canada, this specifically refers to indigenous species threatened with imminent extinction or extirpation over all or a significant portion of their Canadian range.

endemic: An ecological term used to describe species with a local geographic distribution.

energy: The capacity of a body or system to accomplish work, and existing as electromagnetic, kinetic, and potential energies.

energy budget: An analysis of the rates of input and output of energy to a system, plus transformations of energy among its states, including changes in stored quantities.

energy production: See total energy production.

entropy: A physical attribute related to the degree of randomness of the distributions of matter and energy.

environment (the): (1) Refers to influences on organisms and ecosystems, including both non-living (abiotic) and biological factors; (2) An indeterminate word for issues associated with the causes and consequences of environmental damage, or with the larger environmental crisis.

environmental citizenship: Actions taken by individuals and families to lessen their impacts on the environment.

environmental degradation: Refers to pollution, disturbance, resource depletion, lost biodiversity, and other kinds of environmental damage; usually refers to damage occurring accidentally or intentionally as a result of human activities (see also anthropogenic), but can also be caused by natural disasters or stressors.

environmental discrimination (environmental prejudice): Discrimination against any defined group that results in them suffering a disproportionate amount of degradation or pollution of their living or work environment. See also environmental racism.

environmental ecology: See applied ecology

environmental education: A way of fostering environmental literacy by incorporating environmental issues in educational curricula, both in specialized classes as well as across the curriculum, and also including the out-of-school public.

environmental ethics: These deal with the responsibilities of the present human generation to ensure continued access to adequate resources and livelihoods for future generations of people and other species.

environmental impact assessment (EIA): A process used to identify and evaluate the potential consequences of proposed actions or policies for environmental quality. See also socioeconomic impact assessment.

environmental indicators: Relatively simple measurements that are sensitive to changes in the intensity of stressors, and are considered to represent complex aspects of environmental quality.

environmental literacy: Refers to an objective understanding, by individuals and society-at-large, of the causes and consequences of environmental problems.

environmental monitoring: Repeated measurements of indicators related to the inorganic environment or to ecosystem structure and function.

environmental mutagen: A mutagenic influence that is encountered in the environment. See also mutagen.

environmental non-governmental organizations (ENGOs): Charities and other not-for-profit organizations that are working in the environmental field. See also non-governmental organizations.

environmental quality: A notion related to the amounts of toxic chemicals and other stressors in the environment, to the frequency and intensity of disturbances, and to their effects on humans, other species, ecosystems, and economies.

environmental racism: Discrimination against a group of people defined by racial attributes, which results in them suffering a disproportionate amount of degradation or pollution of their living or work environment. See also environmental discrimination.

environmental reporting: Communication of information about changes in environmental quality to interest groups and the general public.

environmental risk: A hazard or probability of suffering damage or misfortune because of exposure to some environmental circumstance.

environmental risk assessment: A quantitative evaluation of the risks associated with an environmental hazard.

environmental science: An interdisciplinary branch of science that investigates questions related to the human population, resources, and damages caused by pollution and disturbance.

environmental scientist: A scientist who is specialized in some aspect of environmental science.

environmental security: The protection of people and the public interest from environmental risks, particularly those associated with anthropogenic activities and accidents, but may also include natural dangers.

environmental stressor: See stressor.

environmental studies: An extremely interdisciplinary approach that examines the scientific, social, and cultural aspects of environmental issues.

environmental teratogen: A teratogenic influence that is encountered in the environment. See also teratogen.

environmental toxicology: The study of environmental factors influencing exposures of organisms to potentially toxic levels of chemicals. Compare with toxicology and ecotoxicology.

environmental values: Perceptions of the worth of environmental components, divided into two broad classes: utilitarian and intrinsic.

environmentalist: Anyone with a significant involvement with environmental issues, usually in an advocacy sense.

erosion: The physical removal of rocks and soil through the combined actions of flowing water, wind, ice, and gravity.

estuary: A coastal, semi-enclosed ecosystem that is open to the sea and has habitats transitional between marine and freshwater conditions.

ethics: The perception of right and wrong. The proper behaviour of people toward each other and toward other species and nature.

eukaryote: Organisms in which the cells have an organized, membrane-bound nucleus containing the genetic material. Compare with prokaryote.

eutrophic: Pertains to waters that are highly productive because they contain a rich supply of nutrients. Compare with oligotrophic and mesotrophic.

eutrophication: Increased primary productivity of an aquatic ecosystem, resulting from nutrient inputs.

evaporation: The change of state of water from a liquid or solid to a gas.

evapotranspiration: Evaporation of water from a landscape. See also transpiration.

evolution: Genetically based changes in populations of organisms, occurring over successive generations.

evolutionary ecology: The interpretation of ecological knowledge in terms of evolution, natural selection, and related themes.

experiment: A controlled test or investigation designed to provide evidence for, or preferably against, a hypothesis about the natural or physical world.

exposure: In ecotoxicology, this refers to the interaction of organisms with an environmental stressor at a particular place and time.

exposure assessment: An investigation of the means by which organisms may encounter a potentially toxic level of a chemical or other environmental stressor.

externality: A cost or benefit that is received, even though the affected party did not choose to incur it.

extant: A species that still exists. Compare with extinct.

extinct (extinction): A condition in which a species or other taxon no longer occurs anywhere on Earth.

extinction crisis: See biodiversity crisis.

extinction vortex: An accelerating spiral of endangerment and extinction caused by worsening environmental conditions.

extirpated (extirpation): A condition in which a species or other taxon no longer occurs in some place or region, but still survives elsewhere.

fact: An event or thing known to have happened, to exist, or to be true. See also hypothesis.

fen: A wetland that develops in cool and wet climates, but is less acidic and more productive than a bog because it has a better nutrient supply. Compare with bog.

first law of thermodynamics: A physical principle stating that energy can undergo transformations among its various states, but it is never created or destroyed; thus, the energy content of the universe remains constant. See also second law of thermodynamics.

First Nations: The Aboriginal people(s) originally living in some place. This term is often used in reference to the original inhabitants of the Americas, prior to the colonization of those regions by Europeans, and their modern descendants.

fission bomb: See atom bomb.

fission reaction: Nuclear reaction involving the splitting of heavier, radioactive atoms into lighter ones, with the release of large quantities of energy.

fitness: The proportional contribution of an individual to the progeny of its population.

flow-through system: A system with an input and an output of energy or mass, plus temporary storage of any difference.

flue-gas desulphurization: A process to remove SO_2 from the waste (flue) gases of a power plant or smelter, before they are discharged into the atmsophere.

flux: A movement of mass or energy between compartments of a material or energy cycle.

food chain: A hierarchical model of feeding relationships among species in an ecosystem.

food web: A complex model of feeding relationships, describing the connections among all food chains within an ecosystem.

food-web magnification (food-web accumulation, food-web concentration): The tendency for top predators in a food web to have the highest residues of certain chemicals, especially organochlorines. Compare with bioaccumulation.

forest floor: Litter and other organic debris lying on top of the mineral soil of a forest.

forestry: The harvesting of trees and management of post-harvest succession to foster the regeneration of another forest.

fossil fuel: Organic-rich geological materials, such as coal, petroleum, and natural gas.

frontier world view: This asserts that humans have a right to exploit nature by consuming natural resources in boundless quantities. See also sustainability world view and spaceship world view.

fuel desulphurization: A process that removes much of the sulphur content of coal before it is used as a fuel in a power plant.

fuel switching: The replacement of a high-sulphur fuel, such as coal, by an energy source that does not emit sulphur gases, such as hydroelectricity or nuclear power.

full-cost accounting system: An accounting system that considers all costs, including those of environmental damage.

fungicide: A pesticide used to protect crop plants and animals from fungi that cause diseases or other damages.

fusion bomb: See hydrogen bomb.

fusion reaction: Nuclear reaction involving the combining of light nuclei, such as those of hydrogen, to make heavier ones, with the release of large quantities of energy. Fusion reactions occur under conditions of intense temperature and pressure, such as within stars and in hydrogen bombs.

Gaia hypothesis: A notion that envisions Earth's species and ecosystems as a "superorganism" that attempts to optimize environmental conditions toward enhancing its own health and survival.

gaseous wastes: The gaseous products of combustion or industrial reactions.

gene: A region of a chromosome, containing a length of DNA that behaves as a particulate unit in inheritance and determines the development of a specific trait.

genocide: The mass killing of an identifiable group as an attempted extermination.

genotype: The genetic complement of an individual organism. See also phenotype.

geography: The study of the features of the surface of the Earth, including topography, landforms, soil, climate, and vegetation, as well as the intersections of these with the economic interests of humans.

geothermal energy: Heat in Earth's crust, which can sometimes be used to provide energy for heating or generation of electricity.

glaciation: An extensive environmental change associated with an extended period of global climatic cooling and characterized by advancing ice sheets.

glacier: A persistent sheet of ice, occurring in the Arctic and Antarctic and at high altitude on mountains.

greater protected area: A protected area plus its immediately surrounding area, co-managed to sustain populations of indigenous species and natural communities.

green manure: Living plant biomass that is grown and then incorporated into the soil by tillage.

green revolution: Intensive agricultural systems involving the cultivation of improved crop varieties in monoculture, and increased use of mechanization, fertilizers, and pesticides.

greenhouse effect: The physical process by which infrared-absorbing gases (such as CO_2) in Earth's atmosphere help to keep the planet warm.

greenhouses gases (GHGs): Atmospheric gases that efficiently absorb infrared radiation and then dissipate some of the thermal energy gain by re-radiation. Synonym: ** radiatively active gases.

gross domestic product (GDP): The total annual value of all goods and services produced domestically within a country. GDP is equivalent to gross national product minus net investment income from foreign countries. See also gross national product (GNP).

gross national product (GNP): The total annual value of all goods and services produced domestically by a country, including net foreign investment income. See also gross domestic product (GDP).

gross primary production (GPP): The fixation of energy by primary producers within an ecosystem. See also respiration, net primary production, and autotroph.

groundwater: Water stored underground in soil and rocks.

groundwater drainage: The drainage of water to storage places in the ground, occurring under the influence of gravity.

growth: Refers to an economy or economic sector that is increasing in size over time. Compare with development.

gymnosperm: Vascular plants such as conifers, which have naked ovules not enclosed within a specialized membrane, and seeds without a seedcoat. Compare with angiosperm.

habitat: The place or "home" where a plant or animal lives, including the specific environmental factors required for its survival.

harvesting effort: The amount of harvesting, which is a function of both the means (such as the kinds of fishing gear) and the intensity (the number of boats and the amount of time each spends fishing).

harvesting mortality: Anthropogenic mortality, especially that due to the harvesting of a bio-resource. Compare with natural mortality.

hazardous waste: Wastes that are flammable, explosive, toxic, or otherwise dangerous. See also toxic waste.

herbicide: A pesticide used to kill weeds. See also weed.

herbivore (or primary consumer): An animal that feeds on plants.

heterotroph: An organism that utilizes living or dead biomass as food.

hidden injury: A reduction in plant productivity caused by exposure to pollutants, but not accompanied by symptoms of acute tissue damages.

high-income countries: Countries with a relatively high average per-capita income. See also developed countries and compare with low-income countries.

hormone: A biochemical produced in an endocrine gland (and transported by the blood) that functions to regulate a metabolic process. Some chemicals in food may mimic the function of hormones produced naturally in the body.

hormonally active substance: A hormone or another chemical that has an effect on the regulation of biochemistry. See also hormone.

humidity: The actual concentration of water in the atmosphere, usually measured in mg/m^3. Compare with relative humidity.

humus: Amorphous, partially decomposed organic matter. An important and persistent type of soil organic matter, it is very important in soil tilth and fertility.

hydrocarbons: Molecules composed of hydrogen and carbon only.

hydroelectric energy: Electricity generated using the kinetic energy.

hydrogen bomb: A nuclear weapon that is based on the fusion of nuclei of deuterium and tritium, two isotopes of hydrogen.

hydrologic (water) cycle: The movement between, and storage of water in, various compartments of the hydrosphere. See also hydrosphere.

hydrosphere: The parts of the planet that contain water, including the oceans, atmosphere, on land, in surface waterbodies, underground, and in organisms.

hyperaccumulator: A species that bioaccumulates metals or other chemicals to extremely high concentrations in their tissues. See also bioaccumulation.

hypereutrophic: Extremely eutrophic waters; usually considered to be a degraded ecological condition. See also eutrophic.

hypersensitivity: An extreme sensitivity to exposure to some environmental factor, resulting in a biological response such as asthma, disease, or even death. It may be expressed at the species or individual level, and it involves responses at relatively low intensities of exposure that the great majority of species or individuals could tolerate.

hypothesis: A proposed explanation for the occurrence or causes of natural phenomena. Scientists formulate hypotheses as statements, and test them through experiments and other forms of research. See also fact.

igneous rock: Rock such as basalt and granite, formed by cooling of molten magma.

impoundment: An area of formerly terrestrial landscape that is flooded behind a dam.

incineration: The combustion of mixed solid wastes to reduce the amount of organic material present.

indicator: See environmental indicator.

indigenous culture: A human culture existing in a place or region prior to its invasion, or other significant influence, by a foreign culture.

individual organism: A genetically and physically discrete living entity.

inductive logic: Logic in which conclusions are objectively developed from the accumulating evidence of experience and the results of experiments. See also deductive logic.

inequitable: Not equitable or fair.

inherent value: See intrinsic value

inhumane: Reflecting a lack of pity or compassion; most commonly refers to the cruel treatment by humans of other animals.

insecticide: A pesticide used to kill insects that are considered pests. See also pesticide and pest.

instrumental value: See utilitarian value

integrated forest management: Forest management plans that accommodate the need to harvest timber from landscapes, while also sustaining other values, such as hunted wildlife, outdoor recreation, and biodiversity.

integrated pest management (IPM): The use of a variety of complementary tactics toward pest control, with the aim of having fewer environmental and health risks.

interdisciplinary: Encompassing a wide diversity of kinds of knowledge.

intrinsic population change: Population change due only to the balance of birth and death rates.

intrinsic value: Value that exists regardless of any direct or indirect value in terms of the needs or welfare of humans.

invasive alien: Refers to non-native species that survive in wild habitats and possibly aggressively out-compete native species or cause other kinds of ecological damage.

inversion: See atmospheric inversion.

invertebrate: Any animal that lacks an internal skeleton, and in particular a backbone.

joule: A standard unit of energy, defined as the energy needed to accelerate 1 kg of mass at 1 m/s2 for a distance of 1 metre. Compare with calorie.

K-selected: Refers to organisms that produce relatively small numbers of large offspring. A great deal of parental investment is made in each progeny, which helps to ensure their establishment and survival. Compare with r-selected.

keystone species: A dominant species in a community, usually a predator, with an influence on structure and function that is highly disproportionate to its biomass.

kinetic energy: Energy associated with motion, including mechanical and thermal types.

knowledge: Information and understanding about the natural world.

landscape: The spatial integration of ecological communities over a large terrestrial area.

landscape ecology: Study of the spatial characteristics and temporal dynamics of communities over large areas of land (landscapes) or water (seascapes).

laws of thermodynamics: Physical principles that govern all transformations of energy. See also first law of thermodynamics and second law of thermodynamics.

leaching: The movement of dissolved substances through the soil with percolating rainwater.

legacy munitions: See unexploded ordinance.

lentic ecosystem: A freshwater ecosystem characterized by nonflowing water, such as a pond or lake. Compare with lotic ecosystem.

less-developed countries: Countries with a relatively well-organized economic infrastructure and a high average per-capita income. See also high-income countries and compare with developed countries.

life form: A grouping of organisms on the basis of their common morphological and physiological characteristics, regardless of their evolutionary relatedness.

life index (production life): The known reserves of a resource divided by its current rate of production.

liming: Treatment of a waterbody or soil to reduce acidity, usually by adding calcium carbonate or calcium hydroxide.

limiting factor: An environmental factor that is the primary restriction on the productivity of autotrophs in an ecosystem. See also Principle of Limiting Factors.

liquid waste: Variable urban wastes that include sewage and discarded industrial and household fluids.

lithification: A geological process in which materials are aggregated, densified, and cemented into new sedimentary rocks.

lithosphere: An approximately 80-km thick region of rigid, relatively light rocks that surround Earth's plastic mantle.

load-on-top (LOT) method: A process used in ocean-going petroleum tankers to separate and contain most oily residues before ballast waters are discharged to the marine environment.

long-range transport of air pollutants: See LRTAP.

lotic ecosystem: A freshwater ecosystem characterized by flowing water, such as a stream or river. Compare with lentic ecosystem.

low-income counties: Countries with a relatively small average per-capita income. See also less-developed countries and compare with high-income countries.

LRTAP: The long-range transport of atmospheric pollutants.

macroclimate: Climatic conditions affecting an extensive area. Compare with microclimate.

macroevolution: The evolution of species or higher taxonomic groups, such as genera, families, or classes. Compare with microevolution.

management system: A variety of management practices used in a coordinated manner.

manipulative experiment: An experiment involving controlled alterations of factors hypothesized to influence phenomena, conducted to investigate whether predicted responses will occur, thereby uncovering causal relationships. See also experiment and natural experiment.

mantle: A less-dense region that encloses Earth's core, and composed of minerals in a hot, plastic state known as magma.

marsh: A productive wetland, typically dominated by species of monocotyledonous angiosperm plants that grow as tall as several metres above the water surface.

mass extinction: An event of synchronous extinction of many species, occurring over a relatively short period of time. May be caused by natural or anthropogenic forces.

maximum sustainable yield (MSY): The largest amount of harvesting that can occur without degrading the productivity of the stock.

mechanization: The use of specialized machinery to perform work, instead of the labour of people or animals.

megacity: A large city, sometimes defined as having a population greater than 8 million people.

mesosphere: The layer of the atmosphere extending beyond the stratosphere to about 75 km above the surface of the Earth. See also stratosphere.

mesotrophic: Pertains to aquatic ecosystems of moderate productivity, intermediate to eutrophic and oligotrophic waters. Compare with eutrophic and oligotrophic.

metal: Any relatively heavy element that in its pure state shares electrons among atoms, and has useful properties such as malleability, high conductivity of electricity and heat, and tensile strength.

metamorphic rock: Rock formed from igneous or sedimentary rocks that have changed in structure under the influences of geological heat and pressure.

meteorite: An extraterrestrial rock-like object; very rarely, one may intersect with Earth's orbit and impact the planet.

microclimate: Climatic conditions on a local scale. Compare with macroclimate.

microdisturbance: Local disruptions that affect small areas within an otherwise intact community. Compare with community-replacing disturbance.

microevolution: Relatively subtle evolutionary changes occurring within a population or species, sometimes within only a few generations, and at most leading to the evolution of races, varieties, or subspecies. Compare with macroevolution.

middle-income countries: Countries with a rapidly increasing average per-capita income. See also high-income and low-income countries and compare with developed countries and less-developed countries.

militarism: A belief of people or governments in the need to maintain a strong military capability to defend or promote national interests.

mitigation: An action that repairs or offsets environmental damages to some degree.

monoculture: The cultivation of only one species while attempting to exclude others from the agroecosystem.

montane forest: A conifer-dominated forest occurring below the alpine zone on mountains.

MSY: See maximum sustainable yield.

mutagen: A chemical or physical agent (e.g., ultraviolet radiation) that is capable of inducing genetic mutations.

mutualism (mutualistic symbiosis): A symbiosis in which both partners benefit.

natural: Refers to a non-anthropogenic context, i.e., one that is not influenced by humans and is self-organizing and dominated by native species; see also nature.

natural capital: See natural resource

natural experiment: An experiment conducted by observing variations of phenomena in nature, and then developing explanations for these through analysis of potential causal mechanisms. See also experiment and manipulative experiment.

natural gas: A gaseous, hydrocarbon-rich mixture mined from certain geological formations.

natural mortality: Mortality due to natural causes. Compare with harvesting mortality.

natural population change: A change in population that is due only to the difference in birth and death rates, and not to immigration or emigration.

natural resource: A source of material or energy that is extracted (harvested) from the environment.

natural selection: A mechanism of evolution, favouring individuals that, for genetically based reasons, are better adapted to coping with environmental opportunities and constraints. These more fit individuals have an improved probability of leaving descendants, ultimately leading to genetically based changes in populations, or evolution.

nature: Refers to the entire system of physical and biological existence and organization, uninfluenced by humans; see also natural.

net ecosystem productivity: The amount of ecosystem-level productivity that remains after respiration is subtracted from gross productivity.

net primary production (NPP): Primary production that remains as biomass after primary producers have accounted for their respiratory needs. See also respiration and gross primary production.

niche: The role of a species within its community.

NIMBY: An acronym for "not in my backyard".

nitrification: The bacterial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-).

nitrogen fixation: The oxidation of nitrogen gas (N_2) to ammonia (NH_3) or nitric oxide (NO).

noise pollution: When the level of ambient sound becomes distracting to the normal activities of people. At a higher intensity it can cause hearing impairment.

non-governmental organizations (NGOs): Charities and other not- for-profit organizations. See also environmental non-governmental organizations.

non-renewable resource (non-renewable natural resource): A resource present on Earth in finite quantities, so as it is used, its future stocks are diminished. Examples are metals and fossil fuels. Compare with renewable resources.

non-target damage: Damage caused by a pesticide to non-target organisms. See also broad-spectrum pesticide and non-target organism.

non-target organism: Organisms that are not pests, but which may be affected by a pesticide treatment. See also broad-spectrum pesticide and non-target damage.

not in my backyard: See NIMBY.

nuclear fuel: Unstable isotopes of uranium (^{235}U) and plutonium (^{239}Pu) that decay through fission, releasing large amounts of energy that can be used to generate electricity.

nuclear winter: A period of prolonged climate cooling that might be caused by a nuclear war.

null hypothesis: A hypothesis that seeks to disprove a hypothesis.

nutrient: Any chemical required for the proper metabolism of organisms.

nutrient budget: A quantitative estimate of the rates of nutrient input and output for an ecosystem, as well as the quantities present and transferred within the system.

nutrient capital: The amount of nutrients present in a site in soil, living vegetation, and dead organic matter.

nutrient cycling: Transfers and chemical transformations of nutrients in ecosystems, including recycling through decomposition.

ocean: The largest hydrological compartment, accounting for about 97% of all water on Earth.

old-growth forest: A late-successional forest characterized by the presence of old trees, an uneven-aged population structure, and a complex physical structure.

oligotrophic: Pertains to aquatic ecosystems that are highly unproductive because of a sparse supply of nutrients. Compare with eutrophic and mesotrophic.

omnivore: An animal that feeds on both plant and animal materials.

organic agriculture: Systems by which crops are grown using natural methods of maintaining soil fertility, and pest-control methods that do not involve synthetic pesticides.

orographic precipitation: Precipitation associated with hilly or mountainous terrain that forces moisture-laden air to rise in altitude and become cooler, causing water vapour to condense into droplets that precipitate as rain or snow.

outer space: Regions beyond the atmosphere of Earth.

over-harvesting (over-exploitation): Unsustainable harvesting of a potentially renewable resource, leading to a decline of its stocks.

oxidizing smog: An event of air pollution rich in ozone, peroxy acetyl nitrate, and other oxidant gases.

paradigm: A pattern or model; a collection of assumptions, concepts, practices, and values that constitutes a way of viewing reality, especially for an intellectual community that shares them.

parameter: One or more constants that determine the form of a mathematical equation. In the linear equation $Y = aX + b$, a and b are parameters, and Y and X are variables. See also variable.

parasitism: A biological relationship involving one species obtaining nourishment from a host, usually without causing its death.

peace: The absence of war.

peace-keeping: An action that occurs after a hot conflict has stopped through a cease-fire agreement, but the conditions for a lasting peace are not yet in place so various means must be used to keep the antagonists apart. Compare with peace-making.

peace-making: The enforced resolution of an active or potential conflict, often by establishing a balanced power relationship among the parties while also imposing a process to achieve a negotiated settlement. Compare with peace-keeping.

persistence: The nature of chemicals, especially pesticides, to remain in the environment before eventually being degraded by microorganisms or physical agents such as sunlight and heat.

pest: Any organism judged to be significantly interfering with some human purpose.

pesticide: A substance used to poison pests. See also pest, fungicide, herbicide, and insecticide.

pesticide treadmill: The inherent reliance of modern agriculture and public-health programs on pesticides, often in increasing quantities, to deal with pest problems.

petroleum (crude oil): A fluid, hydrocarbon-rich mixture mined from certain geological formations.

phenotype: The expressed characteristics of an individual organism, due to genetic and environmental influences on the expression of its specific genetic information. See also genotype.

phenotypic plasticity: The variable expression of genetic information of an individual, depending on environmental influences during development.

photoautotroph: Plants and algae that use sunlight to drive their fixation of energy through photosynthesis. See also chemoautotroph and photosynthesis.

photochemical air pollutants: Ozone, peroxy acetyl nitrate, and other strongly oxidizing gases that form in the atmosphere through complex reactions involving sunlight, hydrocarbons, oxides of nitrogen, and other chemicals.

photosynthesis: Autotrophic productivity that utilizes visible electromagnetic energy (such as sunlight) to drive biosynthesis.

phytoplankton: Microscopic, photosynthetic bacteria and algae that live suspended in the water of lakes and oceans.

plantation: In forestry, these are tree-farms managed for high productivity of wood fibre.

poaching: The illegal harvesting of wild life (plants or animals).

point source: A location where large quantities of pollutants are emitted into the environment, such as a smokestack or sewer outfall.

political ecology: This integrates the concerns of ecology and political economy to consider the dynamic tensions between natural and anthropogenic change, and also the consideration of damage from both natural and anthropogenic perspectives; the latter includes the broad range of concerns from individual people to all of society.

pollution: The exposure of organisms to chemicals or energy in quantities that exceed their tolerance, causing toxicity or other ecological damages. Compare with contamination.

population: In ecology, this refers to individuals of the same species that occur together in time and space.

potential energy: The stored ability to perform work, capable of being transformed into electromagnetic or kinetic energies. Potential energy is associated with gravity, chemicals, compressed gases, electrical potential, magnetism, and the nuclear structure of matter.

potentially renewable natural resource: An alternate phrase for renewable natural resource, highlighting the fact that these can be overexploited, and thereby treated as if they were nonrenewable resources. See also renewable resource.

ppb (part per billion): A unit of concentration, equivalent to 1 microgram per kilogram (μg/kg), or in aqueous solution, 1 μg per litre (μg/L).

ppm (part per million): A unit of concentration, equivalent to 1 milligram per kilogram (mg/kg), or in aqueous solution, 1 mg per litre (mg/L).

prairie: Grassland ecosystems occurring in temperate regions.

precautionary principle: An approach to environmental management, adopted by many countries at the 1992 Earth Summit, which essentially states that scientific uncertainty is not a sufficient reason to postpone control measures when there is a threat of harm to human health or the environment.

precipitation: Deposition of water from the atmosphere as liquid rain, or as solid snow or hail.

precision: The degree of repeatability of a measurement or observation. Compare with accuracy.

prevailing wind: Wind that blows in a dominant direction.

primary consumer: A herbivore, or a heterotrophic organism that feeds on plants or algae.

primary pollutants: Chemicals that are emitted into the environment. Compare with secondary pollutants.

primary producer: An autotrophic organism. Autotrophs are the biological foundation of ecological productivity. See also primary production.

primary production: Productivity by autotrophic organisms, such as plants or algae. Often measured as biomass accumulated over a unit of time, or sometimes by the amount of carbon fixed.

primary sewage treatment: The initial stage of sewage treatment, usually involving the filtering of larger particles from the sewage wastes, settling of suspended solids, and sometimes chlorination to kill pathogens.

Principle of Limiting Factors: A theory stating that ecological productivity (and some other functions) is controlled by whichever environmental factor is present in least supply relative to the demand.

production: An ecological term related to the total yield of biomass from some area or volume of habitat.

production life: See life index.

productivity: An ecological term for production standardized per unit area and time.

prokaryote: Microorganisms without an organized nucleus containing their genetic material. Compare with eukaryote.

protected area (reserve): Parks, ecological reserves, and other tracts set aside from intense development to conserve their natural ecological values. See also greater protected area.

r-selected: Refers to organisms that produce relatively large numbers of small offspring. Little parental investment is made in each offspring, but having large numbers of progeny helps ensure that some will establish and survive. Compare with K-selected.

radiatively active gases (RAGs): Atmospheric gases that efficiently absorb infrared radiation and then dissipate some of the thermal energy gain by reradiation.

rapidly developing countries: Countries with a quickly growing economic infrastructure and a rapidly increasing average per-capita income. See also high-income and low-income countries and compare with developed countries and less-developed countries.

reclamation: Actions undertaken to establish a self-maintaining ecosystem on degraded land, as when a disused industrial site is converted into a permanent cover of vegetation, such as a pasture. Compare with restoration and remediation.

recycling: The processing of discarded materials into useful products.

relative humidity: The atmospheric concentration of water, expressed as a percentage of the saturation value for that temperature.

remediation: Specific actions undertaken to deal with particular problems of environmental quality, such as the liming of acidic lakes and rivers to decrease their ecological damage. Compare with restoration and reclamation.

renewable resource (renewable natural resource): These can regenerate after harvesting, and potentially can be exploited forever. Examples are fresh water, trees, agricultural plants and livestock, and hunted animals. Compare with nonrenewable resources.

replacement fertility rate: The fertility rate that results in the numbers of progeny replacing their parents, with no change in size of the equilibrium population.

replication: The biochemical process occurring prior to cellular division, by which information encoded in DNA is copied to produce additional DNA with the same information.

reserve: (1) Known quantities of resources that can be economically recovered from the environment. (2) An alternative word for a protected area. See protected area.

residence time: (1) The time required for the disappearance of an initial amount; (2) The length of time that a stressor or other environmental influence remains active.

residue: Lingering concentrations of pesticides and certain other chemicals in organisms and the environment.

resilience: The ability of a system to recover from disturbance.

resistance: The ability of a population or community to avoid displacement from some stage of ecological development as a result of disturbance or an intensification of environmental stress. Changes occur after thresholds of resistance to environmental stressors are exceeded.

resource recovery facility: See waste-to-energy facility.

respiration: Physiological processes needed to maintain organisms alive and healthy.

response: In ecotoxicology, this refers to biological or ecological changes caused by exposure to an environmental stressor.

restoration: Establishment of a self-maintaining facsimile of a natural ecosystem on degraded land, as when abandoned farmland is converted back to a native prairie or forest. Compare with reclamation and remediation.

restoration ecology: Activities undertaken by ecologists to repair ecological damage, such as establishing vegetation on degraded habitat, increasing the populations of endangered species, and decreasing the area of threatened ecosystems.

reuse: Finding another use for discarded materials, usually with relatively little modification.

risk: See environmental risks.

risk assessment: See environmental risk assessment.

RNA: The biochemical ribonucleic acid, which is important in translation of the genetic information of DNA into the synthesis of proteins. RNA also stores the genetic information of some viruses.

ruderal: Short-lived but highly fecund plants characteristic of frequently disturbed environments with abundant resources.

run-of-the-river: A hydroelectric development that directly harnesses the flow of a river to drive turbines, without creating a substantial impoundment for water storage.

salinization: The buildup of soluble salts in the soil surface, an important agricultural problem in drier regions.

sanitary landfill: A facility where municipal solid waste is dumped, compacted by heavy machines, and covered with a layer of clean dirt at the end of the day. Some have systems to contain and collect liquid effluent, known as leachate.

science: The systematic and quantitative study of the character and behaviour of the physical and biological world.

scientific creationist: A creationist who attempts to explain some of the discrepancies between his or her beliefs (which are based on a literal interpretation of Genesis) and scientific understanding of the origin and evolution of life. See also creationist.

scientific method: This begins with the identification of a question involving the structure or function of the natural world, usually using inductive logic. The question is interpreted in terms of a theory, and hypotheses are formulated and tested by experiments and observations of nature.

scrubbing: See flue-gas desulphurization.

seascape: A spatial integration of ecological communities over a large marine area.

second law of thermodynamics: A physical principle stating that transformations of energy can occur spontaneously only under conditions in which there is an increase in the entropy (or randomness) of the universe. See also first law of thermodynamics and entropy.

secondary consumer: A carnivore that feeds on primary consumers (or herbivores).

secondary pollutants: Pollutants that are not emitted, but form in the environment by chemical reactions involving emitted chemicals. Compare with primary pollutants.

secondary sewage treatment: Treatment applied to the effluent of primary sewage treatment, usually involving the use of a biological technology to aerobically decompose organic wastes in an engineered environment. The resulting sludge can be used as a soil conditioner, incinerated, or dumped into a landfill. See also primary sewage treatment.

sedimentary rock: Rock formed from precipitated minerals such as calcite, or from lithified particles eroded from other rocks such as sandstone, shale, and conglomerates.

sedimentation: A process by which mass eroded from elsewhere settles to the bottom of rivers, lakes, or an ocean.

seismic sea wave: See tsunami.

selection harvesting: Harvesting of only some trees from a stand, leaving others behind and the forest substantially intact.

sewage treatment: The use of physical filters, chemical treatment, and/or biological treatment to reduce pathogens, organic matter, and nutrients in waste waters containing sewage.

shifting cultivation: An agricultural system in which trees are felled, the woody debris burned, and the land used to grow mixed crops for several years.

significant figures: The number of digits used when reporting data from analyses or calculations.

silvicultural management: The application of practices that increase tree productivity in a managed forest, such as planting seedlings, thinning trees, or applying herbicides to reduce the abundance of weeds.

silviculture: The branch of forestry concerned with the care and tending of trees.

site capability (site quality): The potential of land to sustain the productivity of agricultural crops.

slash-and-burn: An agricultural system that results in a permanent conversion of a forest into crop production, involving cutting and burning the forest followed by continuous use of the land for crops.

slope: The angle of inclination of land, measured in degrees (0° implies a horizontal surface, while 90° is vertical).

SLOSS: An acronym, for single large or several small, in reference to choices in the design of protected areas.

sludge: A solid or semi-solid precipitate that settles from polluted water during treatment; sludge is produced during the treatment of sewage and also in pulp mills and some other industrial facilities. It may be disposed of in a landfill, but if organic, can be used as a beneficial soil amendment.

smog: An event of ground-level air pollution.

snag: A standing dead tree.

social justice: A worldview that calls for equality of consideration for all members of a society, regardless of colour, race, socio-economic class, gender, age, or sexual preference. See also ecological justice.

socio-cultural evolution: See cultural evolution.

socio-economic impact assessment: A process used to identify and evaluate the potential consequences of proposed actions or policies for sociological, economic, and related values. See also environmental impact assessment.

soil: A complex mixture of fragmented rock, organic matter, moisture, gases, and living organisms that covers almost all of Earth's terrestrial landscapes.

soil profile: The vertical stratification of soil on the basis of colour, texture, and chemical qualities.

solar energy: Electromagnetic energy radiated by the sun.

solar system: The sun, its nine orbiting planets, miscellaneous comets, meteors, and other local materials.

solid wastes: Extremely variable municipal wastes that include discarded food, garden discards, newspapers, bottles, cans, construction debris, old cars, and disused furniture.

spaceship Earth: An image of Earth as viewed from space, which illustrates the fact that, except for sunlight, resources needed by humans are present only on that planet.

spaceship world view: This focuses on sustaining only those resources needed by humans and their economy, and it assumes that humans can exert a great degree of control over natural processes and can pilot "spaceship Earth." See also frontier world view and sustainability world view.

special concern: Refers to a species that is not currently threatened but is at risk of becoming so for various reasons.

species: An aggregation of individuals and populations that can potentially interbreed and produce fertile offspring, and is reproductively isolated from other such groups.

speciesism: Discrimination (by humans) against other species purely on the basis that they are not human, especially as manifested by cruelty to or exploitation of animals, or merely by a lack of consideration of their interests.

species richness: The number of species in some area or place.

state-of-the-environment reporting: A governmental, corporate, or NGO function that involves public reporting on environmental conditions.

strategic weapon: Large explosive-yield weapons that are designed to be delivered by a missile or airplane over a distance of thousands of kilometres. Compare with tactical weapon.

stratosphere: The upper atmosphere, extending above the. from 8-17 km to as high as about 50 km. See also troposphere.

stress-tolerator: Long-lived plants adapted to habitats that are marginal in terms of climate, moisture, or nutrient supply, but are infrequently disturbed and therefore stable, such as tundra and desert.

stressor: An environmental factor that constrains the development and productivity of organisms or ecosystems.

succession: A process of community- level recovery following disturbance.

surface flow: Water that moves over the surface of the ground.

surface water: Water that occurs in glaciers, lakes, ponds, rivers, streams, and other surface bodies of water.

sustainability world view: This acknowledges that humans must have access to vital resources, but it asserts that the exploitation of resources should be governed by appropriate ecological, aesthetic, and moral values, and should not deplete the necessary resources. See also frontier world view and spaceship world view.

sustainable development: Refers to progress toward an economic system that uses natural resources in ways that do not deplete their stocks or compromise their availability to future generations.

sustainable economic system (sustainable economy): An economic system that can be maintained over time without any net consumption of natural resources.

swamp: A forested wetland, flooded seasonally or permanently.

symbiosis: An intimate relationship between different species. See also mutualism.

synecology: The study of relationships among species within communities. Compare with autecology.

system: A group or combination of regularly interacting and interdependent elements, which form a collective entity, but one that is more than the sum of its constituents. See also ecosystem.

tactical weapon: Smaller, numerous weapons that are intended for use in a local battlefield, and are delivered by smaller missiles, artillery, aircraft, or torpedoes. Compare with strategic weapon.

taiga: See boreal forest.

tectonic force: Force associated with crustal movements and related geological processes that cause structural deformations of rocks and minerals.

temperate deciduous forest: A forest occurring in relatively moist, temperate climates with short and moderately cold winters and warm summers, and usually composed of a mixture of angiosperm tree species.

temperate grassland: Grass-dominated ecosystems occurring in temperate regions with an annual precipitation of 25–60 cm per year; sufficient to prevent desert from developing but insufficient to support forest.

temperate rainforest: A forest developing in a temperate climate in which winters are mild and precipitation is abundant year-round. Because wildfire is rare, old-growth forests may be common.

temperature inversion: See atmospheric inversion.

teratogen: A chemical or physical agent that induces a developmental abnormality (i.e., a birth defect) in an embryo or fetus.

tertiary sewage treatment: Treatment applied to the effluent of secondary sewage treatment, usually involving a system to remove phosphorus and/or nitrogen from waste waters. See also primary sewage treatment and secondary sewage treatment.

theory: A general term that refers to a set of scientific laws, rules, and explanations supported by a large body of experimental and observational evidence, all leading to robust, internally consistent conclusions.

thermal pollution: An increase in environmental temperature sufficient to result in ecological change.

thermosphere: The layer of the atmosphere extending beyond the mesosphere to 450 km or more above the surface of the Earth. See also mesosphere.

threatened: In Canada, this refers to any indigenous taxa likely to become endangered (in Canada) if factors affecting their vulnerability are not reversed.

tidal energy: Energy that develops in oceanic surface waters because of the gravitational attraction between Earth and the Moon, and can potentially be used to generate electricity.

tilth: The physical structure of soil, closely associated with the concentration of humified organic matter. Tilth is important in water- and nutrient-holding capacity of soil, and is generally beneficial to plant growth.

tolerance: In ecotoxicology, this refers to a genetically based ability of organisms or species to not suffer toxicity when exposed to chemicals or other stressors.

total concentration: The concentrations of metals in soil, sediment, rocks, or water, as determined after dissolving samples in a strongly acidic solution. Compare with available concentration.

total energy production: The use of commercial energy plus traditional fuels in an economy. See also traditional fuels.

total-war economy: An economy that is wholly dedicated to supporting a war effort.

toxic waste: Waste that is poisonous to humans, animals, or plants. See also hazardous waste.

toxicology: The science of the study of poisons, including their chemical nature and their effects on the physiology of organisms. Compare with environmental toxicology and ecotoxicology.

traditional fuels: The non-commercial use of wood, charcoal, animal dung, and other biomass fuels for subsistence purposes, primarily for cooking food and heating homes. See also total energy production and commercial energy production.

transcription: A biochemical process by which the information of double-stranded DNA is encoded on complementary single strands of RNA, which are used to synthesize specific proteins.

translation: A biochemical process occurring on organelles known as ribosomes, in which information encoded in messenger RNA is used to synthesize particular proteins.

transpiration: The evaporation of water from plants. Compare with evapotranspiration.

trophic structure: The organization of productivity in an ecosystem, including the roles of autotrophs, herbivores, carnivores, and detritivores.

troposphere: The lower atmosphere, extending to 8–17 km.

tsunami: A fast-moving, sea-wave caused by an undersea earthquakes, which if large can cause enormous destruction of low-lying coastal places.

tundra: A treeless biome occurring in environments with long, cold winters and short, cool growing seasons.

unexploded ordinance (UXOs): Explosives that remain in place after a conflict has ended.

urban agglomeration: See megacity

urban forest: Urban areas having a substantial density and biomass of trees, although often most are non-native species.

urban planning: An active process of designing better ways of organizing the structure and function of cities, including an orderly siting of land uses and activities.

urbanization: The development of cities and towns on formerly agricultural or natural lands.

utilitarian value: The usefulness of a thing or function to humans.

value added: The increased value of something as a result of manufacturing or some other improvement.

valued ecosystem components (VECs): In environmental impact assessment, these are components of ecosystems perceived to be important to society as economically important resources, as rare or endangered species or communities, or for their cultural or aesthetic significance.

variable: A changeable factor believed to influence a natural phenomenon of interest or that can be manipulated during an experiment.

vascular plant: Relatively complex plants with specialized, tube-like vascular tissues in their stems for conducting water and nutrients.

VECs: See valued ecosystem components.

vector: Species of insects and ticks that transmit pathogens from alternate hosts to people or animals.

vertebrate: Animals with an internal skeleton, and in particular a backbone.

virgin field: In epidemiology, this is a population that is hypersensitive to one or more infectious diseases to which it has not been previously exposed.

volatile organic compounds: Organic compounds that evaporate to the atmosphere at typical environmental temperatures, so they are present in gaseous or vapour forms.

volcano: An opening in Earth's crust from which magmic materials, such as lava, rock fragments, and gases, are ejected into the atmosphere or oceanic waters.

war: A period of organized deadly conflict between human societies, countries, or another defined group.

waste: Any discarded materials. See also hazardous waste and toxic waste.

waste management: The handling of discarded materials using various methods. See also dumping, incineration, recycling, composting, reuse, and waste reduction.

waste prevention: See waste reduction.

waste reduction: Practices intended to reduce the amount of waste that must be disposed of. Also known as waste prevention.

waste-to-energy facility: An incinerator that burns organic waste and uses the heat generated to produce commercial energy.

water cycle: See hydrologic cycle.

watershed: An area of land from which surface water and groundwater flow into a stream, river, or lake.

wave energy: The kinetic energy of oceanic waves, which can be harnessed using specially designed buoys to generate electricity.

weather: The short-term, day-to-day or instantaneous meteorological conditions at a place or region. Compare with climate.

weathering: Physical and chemical processes by which rocks and minerals are broken down by such environmental agents as rain, wind, temperature changes, and biological influences.

weed: An unwanted plant that interferes with some human purpose.

wet deposition: Atmospheric inputs of chemicals with rain and snow. Compare with dry deposition.

wetland: An ecosystem that develops in wet places and is intermediate between aquatic and terrestrial ecosystems. See also bog, fen, marsh, and swamp.

whole-lake experiment: The experimental manipulation of one or more environmental factors in an entire lake.

wind: An air mass moving in Earth's atmosphere.

wind energy: The kinetic energy of moving air masses, which can be tapped and utilized in various ways, including the generation of electricity.

work: In physics, work is defined as the result of a force being applied over a distance.

working hypothesis: A hypothesis being tested in a scientific experiment or another kind of research. See also hypothesis and null hypothesis.

zero population growth (ZPG): When the birth rate plus immigration equal the death rate plus emigration.

zooplankton: Tiny animals that occur in the water column of lakes and oceans