# Ecology: Understanding your World

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## About the Author

Photo: Jack Abler

Rebecca Burton is Professor Emerita of Biology at Alverno College. She received her BS from The Evergreen State College, Her MA from the University of Montana, and her PhD from Kansas State University. She completed post-doctoral studies at the National Center for Ecological Analysis and Synthesis. Her main interests are in behavioral ecology, applied fire ecology, and science pedagogy. She is a former president and Lifetime Honorary Member of the Association of College and University Biology Educators. She volunteers on habitat restoration teams and prescribed burn crews.

# User Guide

**Students:** This book is structured to support your learning:

- **Vocabulary Toolkits** prepare you for reading
- **Learning outcomes** help you focus on the main concepts
- **Section headings** summarize content and provide an outline of the chapter
- **Check Your Understanding** questions keep you on track
- **Analyze the Figure** questions help you make sense of graphs and other images
- **Misconception Alerts** help you avoid common misunderstandings
- **Apply the Concepts** questions help you assess your understanding
- **Case studies** help you apply concepts to relevant situations and issues
- **Appendices** briefly teach important science skills

**Instructors:** This textbook is designed to develop higher-level thinking, using language accessible to all college students. The modular structure allows you to adapt the book to your ecology course.

For courses without science prerequisites, I recommend:

- Assigning Chapters 3 and 4
- Selectively assigning the **Taking it Further** elements
- Selectively assigning **Model Skills**
- Providing discussion of graph analysis and questions

For more advanced courses, consider the following:

- Including the **Taking it Further** elements
- Following the **Hypothesis Testing** activity with exploring the original articles. **Appendix A** is a guide for reading technical articles
- Asking students to compare simplified graphs with the originals
- Selecting which of the **Model Skills** are most relevant to your students

If your course does not have an in-person laboratory, you may wish to have students complete the **Do Try this at Home** activities, which can be completed without special equipment. If your course includes a laboratory, direct your students to the **Appendices** for guides on skills from designing experiments, to analyzing and communicating their findings.

If your course involves exploring multiple frameworks for understanding environmental issues, the **Why it Matters** features could be the basis for short essays or discussions.

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# Ecology: Understanding your world

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## Expanded Table of Contents

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Why it Matters: Intraspecific interactions are critical to conservation
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Parasites take resources from hosts
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Why it Matters: Colony collapse disorder
Evolutionary Perspective: Coevolution, pollinators, and speciation
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Competition results when individuals use similar resources
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Successional stages vary across biomes and microclimates
Make the Medical Connection: Microbial succession in the human gut
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Interspecific relationships influence successional changes
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Stability takes multiple forms
Some species specialize in surviving disturbance
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Proximity to mainland increases island biodiversity
Island biogeography concepts are critical in species conservation
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Global Information System technology can illustrate complex landscape patterns
Make the Medical Connection: Landscape patterns and epidemiology
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Incentives and self interest influence behavior
Regulation can influence human behavior
Make the Medical Connection: Asthma as an environmental justice issue
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Education changes behavior if barriers are low
Appeals to values can influence behavior
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**Unit Outcomes**

Unit I: Knowing the World through Ecology

- Correctly apply concepts of scientific inquiry to gathering and evaluating evidence
- Effectively compare and contrast the science framework with other frameworks
- Describe relevant examples of the role of science and various stakeholders in making management decisions
- Clearly and accurately explain how matter and energy are conserved, transformed, and interact
- Accurately discuss characteristics of living things and their classification
- Correctly apply the concepts of evolution by natural selection including the role of DNA

Unit II: The Non-living World Makes Life Possible

- Accurately describe how energy, water, and nutrients flow through ecosystems
- Correctly apply the laws of thermodynamics to ecosystems
- Apply concepts about heat and states of matter to correctly predict climate, microclimate, vegetation, and soil properties

Unit III: The Living World: Limits of Life

- Accurately describe conditions in different life zones
- Accurately apply ecological concepts to explain and predict abiotic and biotic properties of terrestrial and aquatic life zones
- Clearly explain how ecological and evolutionary factors lead to the distribution of species

Unit IV: Populations

- Use concepts and mathematical models to accurately describe, explain, and predict changes in population size
- Effectively analyze interactions between members of the same species
- Accurately explain how the environment influences patterns of reproduction and lifespan in different species

Unit V: Communities

- Accurately categorize interactions between species as predation, parasitism, commensalism, mutualism, or competition, using valid evidence
- Clearly articulate the influence of interspecific interactions on the species involved
- Accurately explain how disturbances influence ecological communities
- Articulate reasonable explanations for patterns of biodiversity and clearly explain the consequences of this diversity
- Effectively apply concepts of natural selection to community dynamics

Unit VI: The Larger Picture

- Clearly explain how spatial scales influence ecological phenomena such as biodiversity and productivity
- Draw reasonable conclusions about how economic factors and political power influence environmental practices
- Effectively analyze efforts to change human behaviors related to environmental issues

# Unit I

# Knowing the World through Ecology

https://www.fs.usda.gov/research/news/highlights/mount-st.-helens-plays-central-role-field-volcano-ecology

**Ecology is the scientific study of relationships between living things and non-living parts of the environment, such as air, water, soil, nutrients, and energy.**

**Unit Outcomes**

- Correctly apply concepts of scientific inquiry to gathering and evaluating evidence
- Effectively compare and contrast the science framework with other frameworks
- Describe relevant examples of the role of science and various stakeholders in making management decisions
- Clearly and accurately explain how matter and energy are conserved, transformed, and interact
- Accurately discuss characteristics of living things and their classification
- Correctly apply the concepts of evolution by natural selection including the role of DNA

**Unit I: Knowing the World through Ecology**

# Chapter 1: Ecology is a Science

**Case Study Part 1: Are Organic Crops Better for the Environment?**

Figure 1. Sources provide conflicting information about whether organically produced crops are safer for the environment than conventionally produced crops.

Consumers pay billions of dollars for organic fruits, vegetables, and grain every year. Some people may be spending more for organic food because they want to protect the environment. But is there scientific evidence that organically grown crops are better for the environment than conventionally grown crops?

Organic farmers agree to limit the types of pesticides and fertilizers they use. They are not allowed to use genetically modified crops or use radiation to kill germs on produce. In exchange for the right to use the label "organic," they also agree to use some specific farming practices and have additional inspection.

The United States Department of Agriculture says that organic farming helps preserve the environment. Some newspaper and magazine articles say that organic practices keep harmful chemicals out of our soil and water. Other articles say that organic farming wastes more water and uses even more pesticides than traditional agriculture. How does anyone know which sources to trust?

This chapter will discuss how the science of ecology can help answer factual questions about the environment. You will also learn how valid scientific studies are conducted so that you can evaluate which studies are credible.

**Learning from the Case Study**

- What might convince you that one side or the other is correct?
- What sources of information are more believable? Are they the same ones you are likely to use?

# Learning Outcomes

1. *Accurately apply the science framework to the study of ecology*
2. *Design valid experiments*
3. *Draw reasonable conclusions from scientific data*

**Vocabulary Toolkit**

**Roots**

Ecology: Eco = household, ology = study of
Abiotic: A = not, bios = life.

**Opposites**

Biotic and Abiotic
Objective and Subjective
Objective and Biased

**Word Watch List**

**Ecology**: Study of relationships between living and non-living things in the environment
**Abiotic**: Non-living
**Objective**: Not influenced by the observer's emotions or values
**Subjective**: Influenced by the observer's emotions or values
**Quantifiable**: Something that can be measured with a number
**Observation**: Something detected with the senses, including reading a measuring tool
**Inference**: Conclusion based is observations and assumptions
**Hypothesis** (Plural = hypotheses): Guess about the cause of something
**Prediction**: Guess about what will happen in the future, based on data and assumptions
**Law**: Description of patterns that have been widely observed
**Theory**: Explanation of patterns that is strongly supported by multiple lines of evidence. It organizes information and provides useful predictions
**Bias**: Prejudice, lack of objectivity
**Sample Size**: Number of independent data points in an experiment
**Protocol**: Procedure for doing something, such as an experiment
**Independent variable**: Factor that is not caused by the other factor(s)
**Dependent variable**: Factor that may be caused by the independent variable(s)
**Confounding variable**: Factor that is not measured or controlled, but influences a pattern
**Correlation**: Pattern between variables. If both increase together, it is positive. If one increases while the other decreases, it is negative
**Model**: Simplified representation of a real system
**Trendline**: Line showing the relationship between variables
**Causation**: One factor influencing another factor, resulting in a pattern
**Citizen science**: Scientific study conducted by people who are not exclusively professional or highly trained scientists. The word "citizen" in this context is not meant to imply anything about a person's legal status where they live.

**Ecologists Study Relationships in the Environment Scientifically**

**Ecology** is the field of science that studies relationships between living and non-living things in the environment. Ecology is a branch of biology. It involves the study of all living things, whether they are made of one cell or many cells (Figure 2). Ecologists also study non-living, or **abiotic**, things that are essential in understanding the living things. For example, air, water, soil, nutrients, climate, and disturbances like fire are all important topics in ecology.

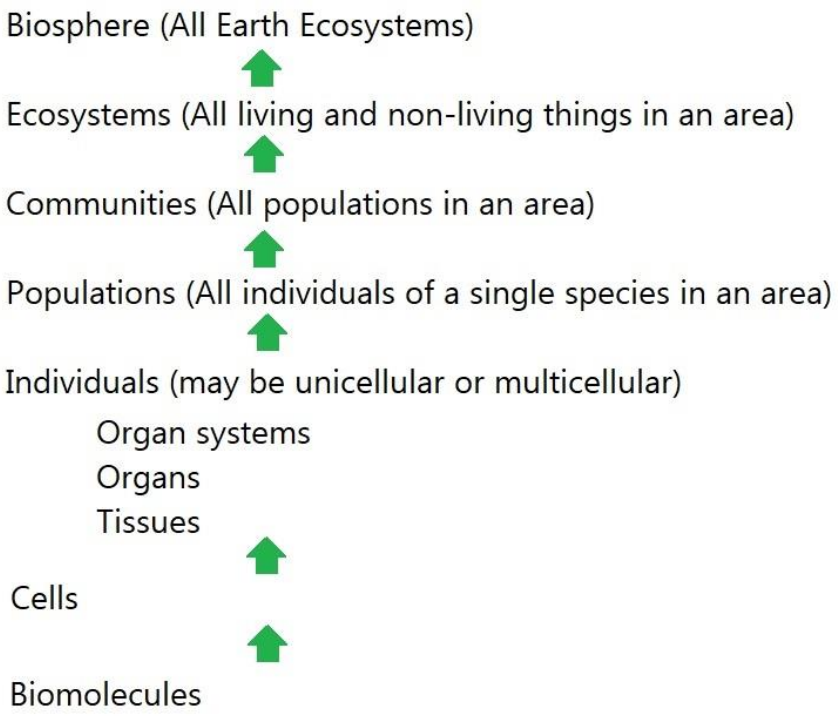



Figure 2. Levels of organization generally studied in ecology. Indented levels apply only to some individuals.

**Analyze the Figure**

- Do communities contain population, or do populations contain communities?
- Are all organisms made of cells?

**Misconception Alert: Ecology is a political viewpoint or movement.**

**FALSE.** Ecology is the scientific study of relationships within ecosystems. These relationships may be between living things or between living and non-living things such as water, light, nutrients, atmosphere, and fire. Ecologists may have personal viewpoints or opinions at any place on the political spectrum. Information from ecology may be used (or misused) in promoting various political actions or policies.

Science assumes that all processes can potentially be explained using natural law. For example, a scientific explanation cannot violate the first law of thermodynamics—that energy can neither be created nor destroyed. Any explanation that relies on supernatural powers or beings is not acceptable in the science framework. Science cannot say whether supernatural forces exist. It cannot tell people what they should do, morally or ethically. It cannot judge beauty. Other frameworks, including religion, philosophy, and art are concerned with these questions. Practice identifying these frameworks using **Do Try this at Home: Ecology Issues**.

**Do Try this at Home: Ecology Issues**

Take a look at a local newspaper or news site. How many articles can you find that have something to do with ecology? Are there local issues about air or water quality, land use, invasive (pest) species, threatened or endangered species, storms, fires, drought, floods, hunting, fishing, or any other topics that involve the ecosystem around you? Are there controversies about these issues? Can science alone provide answers, or do you need to understand economics, culture, politics, law, history, art, or other frameworks? Do you have a personal opinion on any of these issues? What sort of data do different groups use to support their positions? What information would help you to better understand the issues?

Science uses **objective** evidence, meaning that personal opinion does not influence measurements. For example, if 100 people measured the height of your desk with a tool such as a meter stick, all of the measurements would be very similar. If we asked people whether your desk were pretty, we would likely get different opinions. Prettiness is a **subjective** conclusion influenced by observers' experiences, values, and other attributes. Scientific data are usually **quantifiable**, meaning there is a number associated with the measurement, such as the diameter of a tree in centimeters (Figure 3), the temperature of the room in degrees Celsius, or the weight of your lunch in grams.

https://www.nps.gov/im/secn/fofr.htm

Figure 3. Scientists use a variety of tools to gather quantifiable, objective data.

Scientists seek to explain the processes of the universe. **Observations** (Table 1) are experienced directly or measured using tools. One can observe temperature of water using a thermometer. One can observe the song of a bird. **Inferences** are conclusions based on observations, but are not observed directly. One could infer the latitude of a lake based on its temperature range or infer whether it is breeding season for a particular bird species based on their songs.

Table 1. Different categories involving scientific inquiry. Some are descriptive. Some are attempts to explain observations and patterns.

| Descriptive—What? | Explanatory—Why? |
|---|---|
| Observation—What did you experience or measure directly? | Inference—Why did that happen? What caused it? |
| Prediction—What do you expect to observe in this specific situation? | Hypothesis—Why does that happen in general, based on a pattern of observations? |
| Law—What has been observed over and over in many contexts over time? | Theory—Best explanation, based on large body of data from many contexts. Organizes, explains, and predicts many things. |

**Hypotheses** are guesses about how the world works in general. They are potential explanations. They could be attempts to explain the temperatures of lakes or the singing behavior of birds, for example. Scientists use hypotheses to make **predictions** about what will be observed in the future. These would be something like, “If the hypothesis is correct, we would expect to see…” The hypothesis is a *general* explanation for what influences lake temperature, singing in birds, or any other natural occurrence or situation. The prediction is a

*specific* statement about what will happen *in this particular situation* if the hypothesis is correct. If the results match the prediction, you can say they are consistent with the hypothesis. This is evidence that supports the hypothesis. You cannot prove that the hypothesis is correct because there may be other causes that would lead to the same results.

**Misconception Alert: Theories and hypotheses are the same.**

**FALSE.** In everyday language, people tend to say "theory" when they mean "hypothesis" or "prediction." A hypothesis may or may not have been tested. There are an infinite number of hypotheses. A prediction is a guess about what might happen. A hypothesis is a guess about *why* it might happen. A theory is the *best* possible hypothesis known to science after rigorous and extensive testing. It is a major organizing idea. Cell theory—that the cell is the basic unit of life—and the theory of evolution by natural selection are central theories in biology.

**Laws** are descriptions of extremely predictable patterns. For example, the first law of thermodynamics tells us that no one has observed energy coming from nothing or disappearing, so we shouldn't expect it to ever happen. The law does not explain anything. It just tells us what to expect because of what has always happened before. Patterns that are not as consistent are sometimes called rules.

**Misconception Alert: Theories mature into laws.**

**FALSE.** Laws describe things. Theories explain them. The **law** of gravity describes what we expect to happen as an asteroid passes close to Earth and what will happen when your pencil rolls off the desk. The **theory** of gravity is an explanation for *why* objects attract one another and why their mass and the distance between them influence the attraction.

A **theory** is an *explanation* that has been thoroughly tested in multiple contexts. It predicts and explains many things and acts as a major organizing principle. All observations so far fit this explanation, but it can *never* be proven correct. There could always be another explanation that fits the same data. Natural selection is a theory that explains how the observed change in species—evolution—occurs (see **Evolutionary Perspective: Organisms are the Result of Evolution**). It has extensive support and is critical to our understanding of life. Biologists have no other scientific explanation that fits the observed patterns, but there is no way to tell whether there is a better explanation that has not been imagined yet.

**Evolutionary Perspective: Organisms are the Result of Evolution**

*Nothing in Biology Makes Sense Except in the Light of Evolution*
--Theodosius Dobzhansky (1900-1975)

The organizing concept for all of biology, including ecology, is the theory of evolution by natural selection. This concept explains the physiology and behavior of organisms, how they interact, where they are found, and why they have changed. When biologists ask why an organism has particular traits they are asking how the evolutionary history of the species resulted in the set of traits. Chapter 4 will explain natural selection and evolution in more detail.

## Case Study Part 2: Can Science Tell You What to Eat?

https://www.ars.usda.gov/oc/images/photos/oct99/k8502-1/

Figure 4. A small dairy farm in Maryland. Some farms are huge. Farms may produce a variety of products or be monocultures.

Can science be used to test the hypothesis that organic farming is better for the environment than conventional farming? The first step is to decide what objective, quantitative information to collect. This is more complicated than you might think. We have to define what we mean by "better for the environment."

Agriculture influences the environment in many ways. Land used for agriculture is no longer the same kind of habitat is was before. A field of corn does not support the same species as a native grassland or forest. Agriculture uses a lot of water and energy. Farmers use various chemicals to kill organisms that would damage crops, whether the farms are organic or not. Each of these chemicals has its own risks. Fertilizers used on either organic or conventional crops can end up in the water (for more on this issue, see Chapter 9). Farming disturbs the soil, making it more likely to blow away or wash away (for more on this issue, see Chapter 7). Genetically modified crops may need less water, fertilizer or pesticides. A practice that is better in one way may be worse in another.

Which of these factors is the most important to measure? This is subjective. If you live in an area where water is scarce, you may think water use is the most important thing to measure. Another person may be more concerned with avoiding genetically modified crops than conserving water. Another may be more concerned with the efficient use of land, maintaining healthy water for fishing, or preserving native species. These factors usually can't be compared directly. A decrease in water quality is measured on a different scale than an increase in water consumption, for example. A farmer concerned with supporting his or her own family may focus more on either short-term profit or long term value of the land.

Science can provide information on how different crops and practices influence the environment in different ways. It can't tell you which factor is the most important. It can't tell you what you should eat. Your choice will depend on your personal values. The information from a scientific study might help you to decide which behaviors are consistent with your values.

**Learning from the Case Study**

- How would you measure "harm" to the environment? Why might another person measure it in a different way?
- Why can't science tell you what you *should* do?

**Check Your Understanding**

- How is the evidence that is acceptable in science different from evidence that might be acceptable in other frameworks, such as art, politics, or religion?
- How are theories different from hypotheses, predictions, and laws?
- Can you ever prove a hypothesis correct?

## Scientists Test Hypotheses Systematically

Your high school science textbook probably contained an illustration of a sequence of events called the scientific method. The steps are usually presented in a linear sequence of observation, question, hypothesis, experiment, and conclusion. This is a good starting point for understanding how science works, but the reality is rarely this simple. Multiple hypotheses are usually tested at the same time. Hypotheses may be formulated after an experiment or change

during the development of methods. Even though any particular study might happen in a unique way, scientists use a system for designing their tests (for a summary of experimental design, see Appendix B).

Scientists can be influenced by their own opinions, even when they try to be objective. **Bias** is the tendency for people to evaluate things according to their own assumptions or values. Good experimental designs reduce bias in measurement. For example, algae levels in lakes (Figure 5) can be a major environmental, health, and economic issue. Suppose that that there is less algae than usual growing in a lake and that the lake temperature is below average for that time of year. One could hypothesize that cooler lake temperatures cause lower algae growth. In other words, one might *explain* algae levels by saying they are influenced by lake temperature. A scientist (or team of scientists) must be careful not to bias the experiment in any way that would unfairly support or refute that hypothesis. For more on bias, see **Hypothesis Testing: Do Biases Prevent Fair Evaluation of Issues?**

http://www.ecy.wa.gov/programs/wq/plants/algae/monitoring/SteilacoomBloom.html

Figure 5. Algae (tiny green organisms) growing in a Washington lake. Like plants, algae do photosynthesis. They need sunlight and nutrients to grow.

Let's assume that a team of scientists predicts that there will be a consistent pattern of lower algae growth when water temperatures are lower. The team cannot measure algae and temperature of every possible lake, every location on every lake, at every time of day, and every day of the year. Instead, they try to get a fair and representative sample. If the researchers want to generalize their results to all of the lakes in their county, for example, every lake in their county must have an equal chance of being included in the sample. A random sample prevents researchers from unconsciously choosing samples that will support their hypothesis.

**Misconception Alert: Random means sloppy or unplanned.**

**FALSE.** In science, a random sample means that every individual in a group has an equal chance of being selected. Putting names of all the lakes on index cards, mixing them up, and picking 10 of them would be random. Looking at a map and just picking ten would not be random. A random sample takes careful planning.

The number of independent data points collected is called the **sample size**. Larger sample sizes are better because in a larger sample, an extreme value is more likely to be balanced by other values. Taking multiple readings at Pine Lake and multiple readings at Duck Lake still gives you a sample size of two because the multiple samples in each are not independent.

Researchers must decide in advance on the **protocols** or procedures for finding measurement sites, depth of the samples, and other practices. Clear protocols promote consistent, unbiased measurements. Suppose a temperature measurement at a lake seems a bit low. It is not ethical to discard the data point and try to find a warmer place.

To test whether one **independent variable** (lake temperature in this case) influences the **dependent variable** (algae level in this case), you must control the other variables as much as possible. Taking the samples in the morning for one set of lakes and night for another would introduce time of day as a **confounding variable**.

Suppose that data collected in many lakes or over several years showed a pattern of less algae when lake temperatures were cooler. This would be a **correlation** between algae level and temperature (See **Model Skill: Correlations)**. Finding a correlation between the variables would support the hypothesis that cooler temperatures caused less algae growth, but there could be other valid explanations. One can *never* prove that a hypothesis is correct.

In this example, maybe there is more algae growth in warmer years because there is more sunshine. The sunshine could have caused both the increase in algae and the warmer lake. Maybe people water their lawns more often in warm weather. This could wash more nutrients into the lake and increase algae growth. There may be other explanations, even ones that no one has thought of yet. Would the idea that warmer water leads to higher algae levels now be a theory? No. Theories are central concepts with extensive evidence from many contexts. What the researcher would have is a hypothesis that was supported by some evidence.

When ecologists can manipulate the variables directly, it is easier to control possible confounding variables. For example, researchers could control the temperature in different tanks of algae in a laboratory.

**Model Skill: Correlations**

Scientists use **models**—simplified representations of the real world—to study and communicate data and ideas. A model can be a picture, a graph, an equation, a computer simulation, or even a physical model, such as a "river" built on a table. By definition, the model will lack some of the detail of the real world, but it can often show patterns that would be difficult to see or understand otherwise.

Imagine that researchers wanted to use a graphical model to show data on average depth and average temperature on several lakes in an area (Figure 6). They hypothesize that deeper lakes tend to be colder because the heat from the Sun is spread throughout a larger volume of water. The depth of the lakes is the independent variable because the researchers hypothesized that the depth would explain the difference between the lakes. The independent variable is plotted on the horizontal, or X-axis of a scatterplot. Temperature is the dependent variable because the researchers hypothesize that it depends on lake depth. In other words, the depth of the lake might influence the temperature of the lake, but the temperature of the lake will not make it deeper or shallower. The dependent variable is usually plotted on the vertical, or Y-axis.

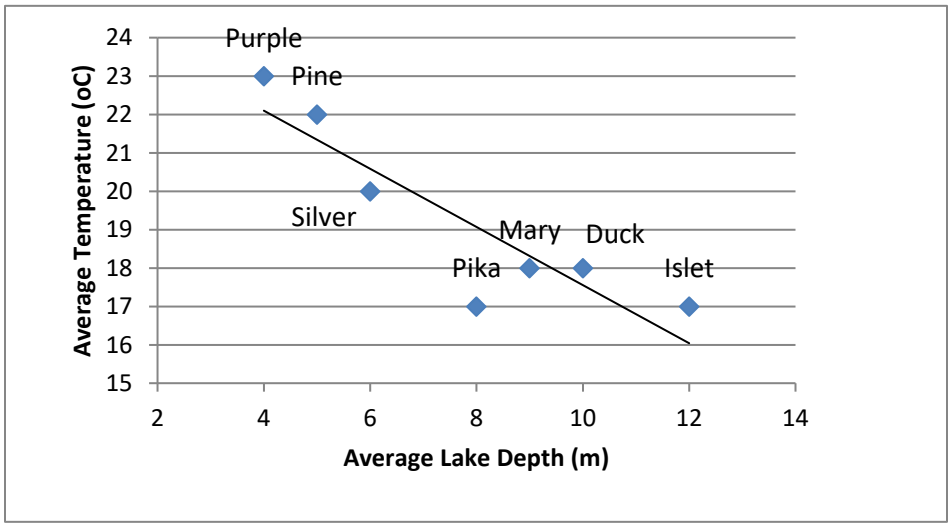



Figure 6. Scatterplot showing hypothetical depths and temperatures of lakes in an area. Each blue diamond represents one lake. The black line is a model that shows the general trend of the data. Labels give the names of individual lakes.

**Analyze the Figure**

- Identify the independent and dependent variables.
- What is the general trend of the data?
- What is the difference between the line and the data points?

**Continued**

**Model Skill: Correlations, cont.**

Each data point shows average depth and temperature for one lake. A **trendline** shows the general pattern of the data. The trendline does not connect the dots. It is a model that reduces the complexity of all the dots into one line that can be described by an equation. What pattern do you see in the data? To describe the pattern, try using the axis labels, with the horizontal or X-axis first, then the vertical or Y-axis. For example, "As the average lake depth increases, the average temperature [decreases, increases, or stays the same]." You will practice making your own scatterplots to show correlations in Chapter 16.

It is tempting to interpret a correlation like the one in Figure 6 as demonstrating that the independent variable caused the pattern in the dependent variable. This may be correct, but correlation does not prove **causation**. It is possible that the pattern is a coincidence. It is also possible that the lake depth and temperature are caused by a confounding variable. For example, maybe it is warmer in the southern part of the county and that is where the shallower lakes are. The location of the lakes would be a confounding variable that influenced the results. The location of the lakes could be seen by looking at a map, but not all confounding variables are this obvious. Since changing the size of the lakes is probably not practical, the only way to study the effect of a variable is through a correlation study. For other patterns that must be studied using correlations, see **Make the Medical Connection: Correlations and Environmental Health Risks**.

**Hypothesis Testing: Do Biases Prevent Fair Evaluation of Issues?**

Do people need to protect themselves from their own biases? Perhaps honest and intelligent people can trust themselves to conduct research without the need for randomization and double-blind studies. Can people really evaluate controversies fairly if they just try to keep an open mind?

Taber and Lodge (2006) investigated this question. They were interested in multiple hypotheses about how different biases might influence how people searched for and evaluated arguments and information on controversial topics.

Hypothesis 1: People will have a prior attitude effect, causing them to evaluate evidence that agrees with their position as being stronger than evidence that disagrees with their position.

Hypothesis 2: People will work harder to challenge evidence that disagrees with their position than evidence that agrees with their position.

Hypothesis 3: People will have a confirmation bias that leads them to seek out information that confirms their position and limit their exposure to information that refutes their position.

Taber and Lodge (2006) recruited volunteer undergraduate students to complete an online exercise under controlled conditions. First, subjects were asked a series of questions to

determine their positions on two controversial topics. Participants were then told to find information so that they could provide an unbiased explanation of the issue to their peers. The computer provided links to 16 policy arguments. Each link was labelled as being from a source that had a known position on the issue. Participants received descriptions of the sources and were tested on the descriptions. Participants could look at any 8 of the 16 policy arguments. Then the participants re-took the survey on their own positions and answered several other questions to determine their political knowledge and other information.

Participants completed a second study on a new topic. First, they ranked the strength of 8 arguments. Half of the arguments supported one side of the controversy; half supported the other side. Participants were told to rank the quality of the arguments fairly, without bias. They then took a test on their attitudes and memory of the topic and wrote down some thoughts on the issue. The data were analyzed with participants grouped by their position on the controversy and other variables. One grouping was people who were classified as politically sophisticated (Figure 7).

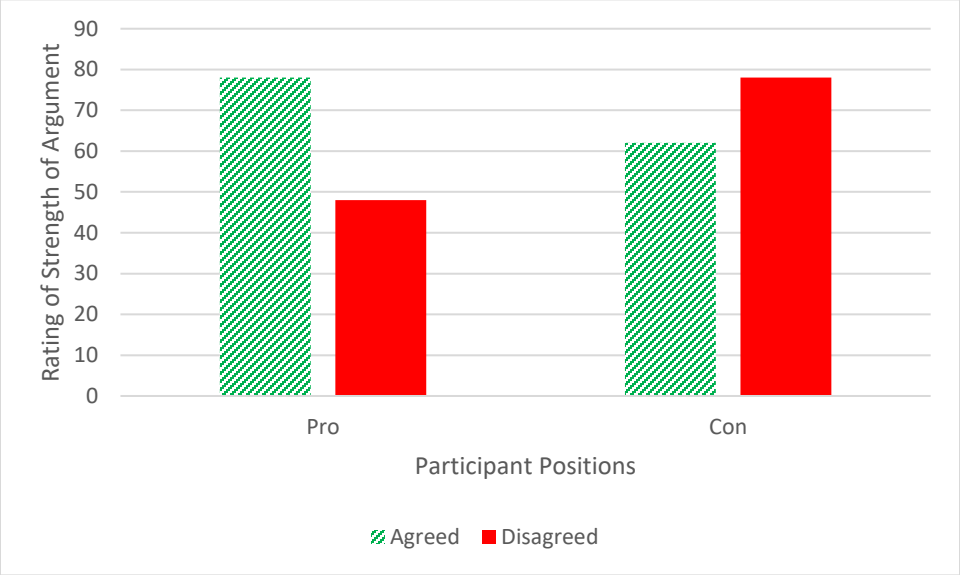



Figure 7. Participants' ratings of the strength of arguments. Bars labeled Pro represent subjects who were in favor of the policy. Bars labeled con represent students who were against that policy. Green cross-hatched bars show how subjects rated arguments that agreed with their positions. Solid red bars show how subjects rated arguments that disagreed with their positions. These participants were classified as politically sophisticated. Modified from: Taber, C. S., & Lodge, M. (2006). Motivated skepticism in the evaluation of political beliefs. *American Journal of Political Science*, *50*(3), 755-769.

**Analyze the Figure**

- Did participants tend to rate arguments with which they agreed higher than arguments with which they disagreed?

- Which of the hypotheses are supported or refuted by this data set?

Researchers assumed that time spent reading an argument was related to participants trying to find flaws with those arguments. If the time spent were a function of needing more time to understand the arguments, then participants with less knowledge would be expected to spend more time reading than students with more knowledge. People with strong feelings about an issue may be expected to show a greater bias (Figure 8).

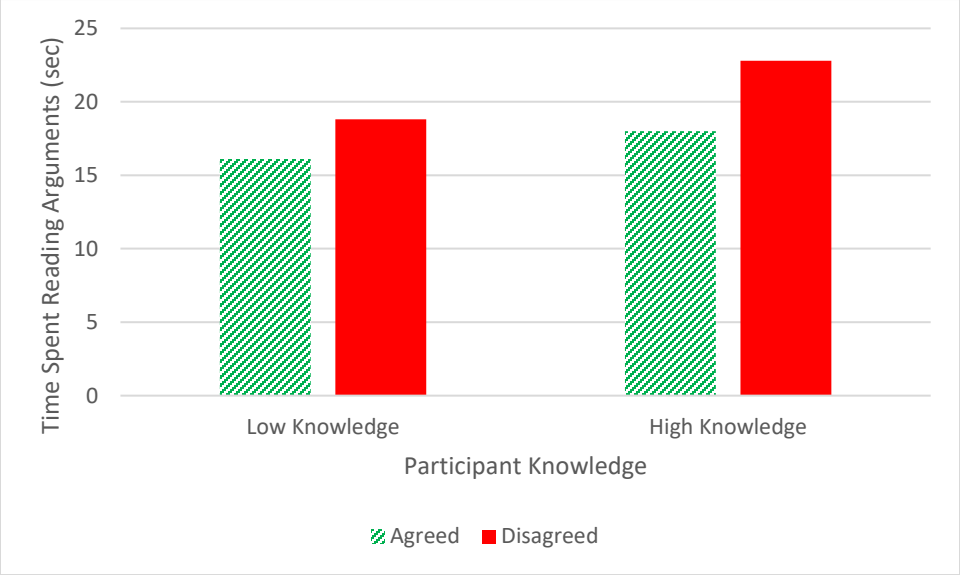



Figure 8. Time participants spent reading arguments that agreed (green crosshatch) with their positions or disagreed (solid red) with their positions. Participants were grouped by their understanding of the issue (low knowledge or high knowledge). Modified from: Taber, C. S., & Lodge, M. (2006). Motivated skepticism in the evaluation of political beliefs. *American Journal of Political Science*, *50*(3), 755-769.

**Analyze the Figure**

- Did participants tend to spend more time reading arguments with which they agreed or arguments with which they disagreed?
- How did participants' knowledge influence their time spent reading arguments?
- Which of the hypotheses are supported or refuted by this data set?

Researchers also analyzed whether participants tended to select arguments that supported their own positions when they were allowed to choose 4 of 8 arguments (Figure 9).

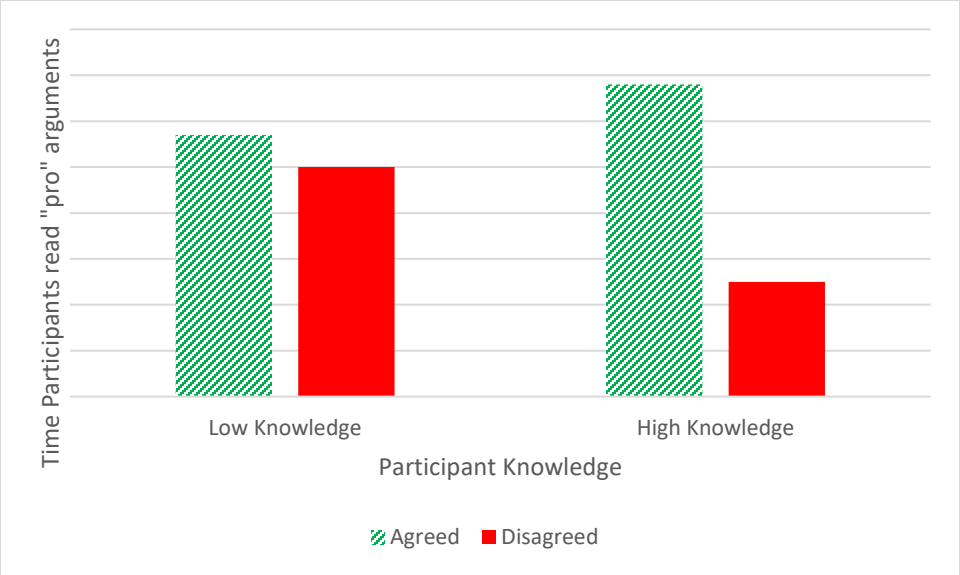



Figure 9. Proportional time that participants elected to read "pro" arguments regarding an issue. Green cross-hatched bars show subjects that had a “pro” position. Solid red bars show how subjects that had “con” positions. These participants were classified as having strong positions on the issue. Modified from: Taber, C. S., & Lodge, M. (2006). Motivated skepticism in the evaluation of political beliefs. *American Journal of Political Science*, *50*(3), 755-769.

**Analyze the Figure**

- Did participants decide to view a greater proportion of arguments with which they agreed compared to arguments with which they disagreed?
- How did participants' knowledge influence their selection of arguments?
- Which of the hypotheses are supported or refuted by this data set?

**Evaluate the Hypotheses**

- Which of the hypotheses were supported by the data?
- The topics used in this study were gun control and affirmative action. Is there any reason to think the pattern would be different for environmental issues? Explain your reasoning.
- Do the findings of this experiment provide evidence that systematic data collection is necessary to combat biases in experimenters?

**Case Study Part 3. Does Organic Farming Protect Butterflies?**

Loss of habitat and changing climate patterns threaten many butterfly species in England (for more information on where species are found, and how that changes, see Chapter 10). For example, the high brown fritillary (*Fabriciana adippe*) was common in England but has become rare due to losses in habitat and increases in rainy weather. Some of the lost habitat is now agricultural fields. How might you measure whether organic farming is less harmful to butterflies than conventional farming?

One team of researchers measured how grain crops in England influenced the number of individuals and species of plants and animals, including butterflies (See Chapter 17 for more on species diversity). Ecologists needed an unbiased way to select the farm fields to include in their study. They could not take a random sample from all of England, but they used a complicated process and maps of the landscape to match organic and non-organic farming areas for 30 different variables, such as climate, soil, and the socio-economic status of the communities (See Chapter 18 for more on landscape-level patterns). Researchers used a protocol to help them be consistent as they walked through the fields and counted the number and type of butterflies they saw in 15 minutes (Figure 11). They did this at 262 conventional fields and 188 organic fields.

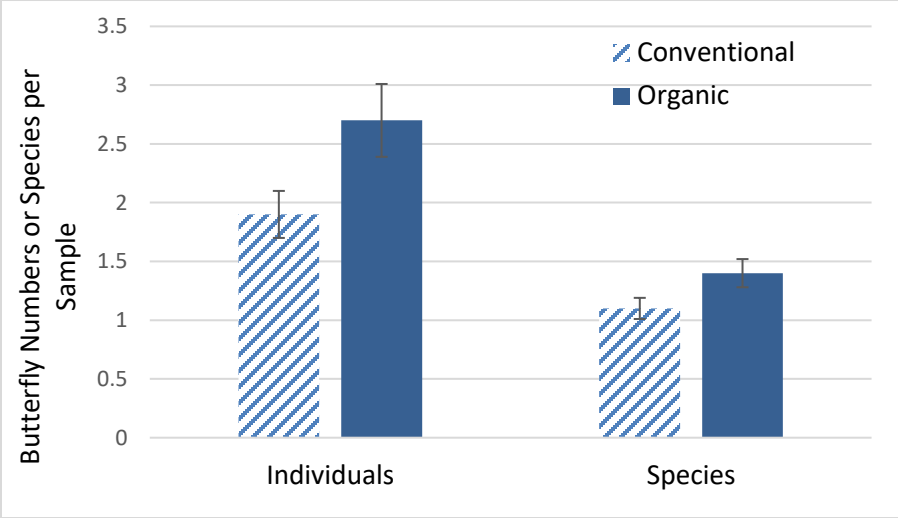



Figure 11. Comparison of number of butterflies or butterfly species on organic and conventional fields in England. Samples were 15-minute walks. The height of the bars shows the average (mean). The lines that cross at the mean represent variation between samples. Based on data from: Gabriel, D., Sait, S. M., Kunin, W. E., & Benton, T. G. (2013). Food production vs. biodiversity: comparing organic and conventional agriculture. *Journal of Applied Ecology*, *50*(2), 355-364.

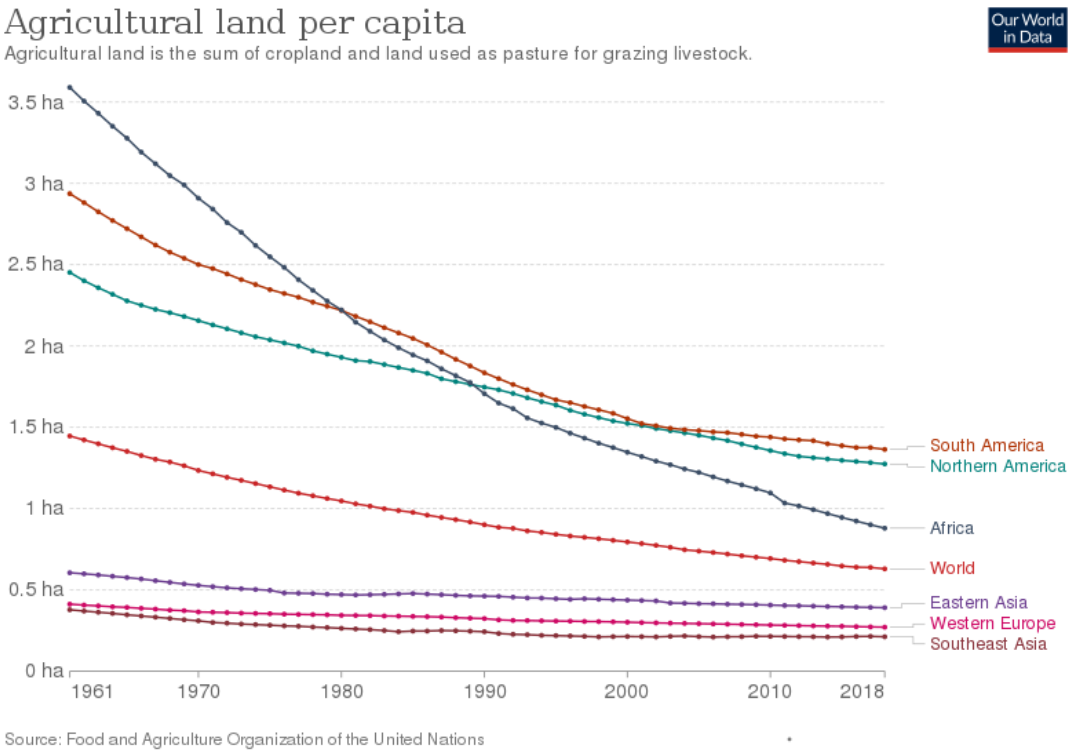
**Analyze the Figure** (**Appendix D** has advice on reading graphs)**:**

- Which fields had more individual butterflies?
- Which fields had more butterfly species?
- Identify the independent and dependent variables.

The study generally found more species—including butterfly species—on the organic fields. Fields that had a lot of organic fields nearby had more species than fields that had a lot of conventional fields nearby. Did this study prove that organic farming will help to preserve English butterfly species?

When the researchers looked at the effect of a possible confounding variable—crop yield—they found a different pattern. Crop yield is measured as the amount of the crop—grain in this case—produced per unit area. Some factors that influence yield are fertilizer levels, pesticide use, and how often the farmer changes types of crops grown in a field. Researchers found a negative correlation between crop yield and the number of individual butterflies or the number of butterfly species.

Because the organic fields had lower yields, the data suggested that it was the farming practice that caused the difference. If farmers used less-intensive methods—whether they were organic or conventional—the land would support more butterflies. Some people might argue for less-intensive agriculture, but others might point out that more habitat would have to be converted to farmland to feed the same number of people if crop yield decreased. Agricultural land is a finite resource (Fig. 12).




https://commons.wikimedia.org/wiki/File:Agricultural-area-per-capita.svg

Figure 12. The amount of agricultural land per person in different parts of the world.

**Analyze the Figure:**

- Which areas of the world have the most agricultural land per capita?
- Which regions have had the fastest decline in per capita agricultural land since 1961?
- Are any regions experiencing an increase in per capita agricultural land?

**Learning from the Case Study**

- Why didn't the researchers just make measurements on several organic farms and several conventional farms? Why go to all the trouble of having matched high-organic and low-organic plots near each other?
- Explain how the results of the study influenced your conclusions about whether organic grain farming helps protect English butterflies.
- Explain how evaluating the environmental impact of organic farming depends on which variables are selected and studied.

**Make the Medical Connection: Correlations and Environmental Health Risks**

https://www.epa.gov/radtown/electric-and-magnetic-fields-power-lines

Figure 13. High-voltage power lines.

How does our environment influence our health? This important question is difficult to answer. Suppose you thought that living near power lines would increase a person's cancer risk. How would you test this hypothesis? The best experimental design would be to take a large group of people, randomly assign them to living different distances from power lines and keep everything else about them as similar as possible. Then you would observe them for a few decades and see how many cancers occurred in people living different distances from power lines. Does this seem likely to ever happen?

When scientists want to study the effect of environmental variables on health, they are usually forced to look for patterns in data about health problems. This is called an epidemiological study. It is a search for correlations between health problems and potential independent variables that may have influenced health. The problem with these studies is that there is no way to control the many confounding variables that may have caused the health problem. Imagine that cancer deaths were higher in people living under power lines. Does that mean the power lines caused the cancer? Maybe poverty is a confounding variable and people who can only afford housing under power lines also can't afford good health care (see **Model Skill: Correlations** for more discussion of confounding variables).

Epidemiological studies will always have flaws, but they are often the only data we have. They tend to be more convincing when similar patterns are found after controlling for any confounding variables that the researchers can identify (for example, if they only include people with similar incomes or use statistical tests that can control for income level). Unfortunately, there may still be confounding variables that the researchers didn't recognize. Epidemiological studies and other studies that rely on correlation should always be interpreted especially carefully.

**Check Your Understanding**

- Why is a large sample size important?
- What are some ways researchers control for bias in a study?
- How can confounding variables influence a study?

## Scientists Share Professional Values

The scientific community values honesty. As individuals, scientists may not be any more or less honest than people in any other profession, but dishonesty in reporting methods or results in science will end a career. Science builds on past discoveries, so false information undermines scientific progress. Public policy and health decisions may be influenced by bad information. Researchers who were found to have been dishonest have been fired and have had their doctoral degrees invalidated, even when there was no evidence they were dishonest in the work they did to earn their degrees. Dishonest research is likely to be discovered. Scientists are expected to publish their work and to fully describe what they did and found (for more on this process, see **Taking it Further: Peer Review**). The more interesting and important a finding is, the more likely it is that others will try to repeat the research. If they get different answers, and no reason for those differences can be found, questions will be asked about the original report.

Precision is important in procedures, measurement, and communication. Small variations and misunderstandings can have major consequences, so sloppiness is unacceptable. Scientific progress depends on precise, reliable information about what has been done and found.

Scientists are expected to report their findings accurately, even if their findings will be unpopular. A scientist is bound by ethical rules such as those regarding the treatment of human subjects or animals, but science is not supposed to be confined to “safe” topics or hide unwanted results.

Scientists generally value creativity, persistence, skill at analyzing problems, and the ability to work in teams. Creativity is essential to developing important questions, new hypotheses, and methods for testing those hypotheses. Persistence is also critical because there are often many difficulties in developing methods and many hypotheses will be discarded. Effective research usually requires effective teamwork because the logistics of ecological research can be demanding.

Ecologists may find themselves working at the bottom of the ocean, in a laboratory, at the top of a tropical tree, in front of a classroom, on a glacier, in a government office, or in front of a computer monitor. Regardless of where they work, they are expected to respect the ethics of the scientific community.

**Taking it Further: Peer Review**

Scientists are usually expected to publish their work in peer-reviewed journals or books. These are often published by professional societies. For example, the Ecological Society of America publishes the journal *Ecology*. When a researcher or team of researchers send an article to a scientific journal, the editor identifies appropriate scientists to review the article. The editor is a respected scientist but is not an expert in every topic in ecology. If a scientist agrees to review the article, they carefully evaluate it using a variety of criteria, such as:

- Will the topic be interesting to the readers of the journal (relevant and important)?
- Do the authors explain the context of the experiment clearly and thoroughly (such as why it is important and what others have found)?
- Are the methods clear and valid?
- Are the results presented clearly?
- Do the results support the conclusions of the authors?
- Do the authors clearly and completely explain how their results compare with the findings of others?
- Is the paper readable, and does it follow conventions for grammar, spelling, and format?
- Did the authors follow legal and professional guidelines?

The reviewer may recommend that the paper be accepted as it is. Few papers are flawless, so they are still likely to have minor revisions to suggest. If the reviewer finds that the paper has merit but needs some substantial work, they will probably recommend that it be accepted with major revisions. If the reviewer finds that the methods were flawed, the findings were not important, or the topic is not relevant to the readers of the journal, they will recommend that it be rejected, but they may have suggestions for other places to publish or different ways to improve the work. If the authors failed to get required permits or approval for the study, the article will be rejected and further action may be taken.

Some of these criteria are subjective, so the reviewers may have different opinions. The editor makes the final decision, but usually sends all of the reviewers' comments to the authors. To reduce bias, journals usually allow reviewers to remain anonymous and may not reveal the identity of the authors to the reviewers. If a reviewer has any potential conflict of interest, they are expected to inform the editor.

**Continued**

**Taking It Further: Peer Review, continued**

If the author(s) resubmit the paper, they are expected to address the changes that the editor and reviewers suggested. If reviewers disagreed on something, the authors are expected to explain which recommendations they followed and why they did so. Wise authors treat all reviewers' comments as feedback that can improve their work. The revised paper may go back to the original reviewers, out to new reviewers, or be evaluated by the editor. A similar process is used for peer-reviewed books and book chapters.

This process is not perfect, but it helps to ensure that well-informed experts in a field have evaluated the work and found it to be scientifically valid. It also improves the quality of scientific writing, ideally making it clearer, more accurate, and more precise. Authors who do not follow professional ethics guidelines—such as getting approval for research that uses animals—will be unable to publish their research.

For more information on the structure and content of scientific papers, see Appendices A and F.

**Misconception Alert: Ecologists only work in natural areas.**

**FALSE.** While people may have many definitions of what "natural" areas are, ecologists work in all sorts of areas, from the largest cities to the remotest wilderness. The phrase "urban ecology" is often used to describe work on studies such as movement of coyote-wolf hybrids into cities and suburbs, how green spaces decrease crime rates, or the effect of dam removal on neighborhood water quality.

Although they share many professional values, scientists have diverse interests, perspectives, and talents. This diversity is essential to scientific progress. It is impossible to know where the next important hypothesis, idea for testing, or method for analyzing the data will come from. If everyone thought the same way, the chances for an exciting new idea or approach would be much lower.

Researchers may study a particular question for a variety of reasons, including personal interest, availability of funding, requirements of their job, or convenience. Scientists who work for industry are often assigned projects by their companies. Government scientists work on projects assigned by their agency. Researchers at non-governmental organizations (NGOs) typically do research that supports the specific mission of their organizations. Scientists at universities and colleges potentially have a lot of freedom to determine their projects, but most research requires funding by government agencies or private foundations. Funding of scientific research is often determined by a variety of factors, including economics, politics, and public relations. No matter why they are doing the experiment or where the funding is from, scientists are expected to be ethical in how they conduct and report their experiments.

**Case Study Part 4. Are Organic Crops Better for the Environment?**

https://content.govdelivery.com/accounts/USDAAMS/bulletins/37570fa

Figure 14. Agricultural products can be certified organic by the USDA.

Important questions rarely have simple answers. As you have seen, part of the answer depends on how you ask the question. Which dependent variable do you think is most important, soil, water, energy, species diversity, or some other factor? The answer will also depend on the specific area studied, the specific crops involved, and the specific farming practices used. While it's tempting to just say that all organic farming is better, worse, or no different from conventional farming, this would be cheating yourself of the whole story.

When researchers looked at many comparisons between organic and conventional farms in Europe they found some consistent differences. Organic farms tend to have more nutrients in the soil. They may also support more species. They also use less energy. However, they do not produce as much food per area, meaning that more habitat may have to be converted to farmland if more farmers use organic methods. Organic farms also lose more nutrients from the soil per each unit of food produced.

This complexity does not mean that science cannot provide useful information or that some scientists are lying. It does mean that a person must be precise about what they want to know. Then they have to use that information appropriately.

**Learning from the Case Study**

- What factors might lead to a different answer about whether an organically produced food is better for the environment and a conventionally produced one?
- Why might people who value the environment equally make different decisions about purchasing organic or conventional foods?

**Why It Matters: You Can Decide for Yourself**

https://new.nsf.gov/about/congress

Figure 15. If you understand how to evaluate scientific evidence, you can better advocate for yourself and your community.

When you understand the process of science, you have much more power to make decisions that reflect your values. In the past, it was difficult for a citizen to get enough information to be well informed about scientific issues. Now information is readily available. The challenge is to be a good consumer of information. Knowledge alone is not nearly as powerful as the ability to evaluate knowledge and understand its implications. You can read scientific studies for yourself. You can evaluate both the methods that the researchers used and the conclusions they made based on their data. Then you can make informed decisions that influence your life.

- Have you ever relied on a person or organization to interpret a scientific issue for you, and then found out that their interpretation was wrong?
- What might motivate someone to present a biased view of an environmental issue?
- How does the ability to understand environmental controversies give you power?

**Check Your Understanding**

- Why are honesty and precision important in science?
- Why are creativity and persistence important for a scientist?

**Anyone Can Study Ecology**

In early human history, everyone was an ecologist. Survival depended on knowing where plants grew, what animals did, how to find water, and which clouds meant a storm. In agricultural societies, understanding ecology helped people make good decisions about their land and the species on it. In any society, people who had the time might study species or areas that interested them. As science became a profession, it became common to assume that only professional scientists could "do science." This view is changing.

Projects that include a variety of people who are not professional scientists are called **citizen science** or **community science** projects. Paricipants might be school children recording the dates when certain flowers begin to bloom, retired people banding birds, or mixed groups of amateurs and professionals carrying out complicated long-term studies (Fig. 16).

https://www.nps.gov/subjects/citizenscience/citizen-science.htm

Figure 16. Participants in citizen science.

All of those involved in citizen science have something to contribute. Scientists spend years learning the history, concepts, and practices of their discipline. Their expertise is useful in deciding which experiments will be new, making sure that the methods of the study are valid, interpreting results, and communicating them effectively. Some people with little or no scientific training are self-taught experts in identifying species or some other skill. With a little training,

most people can perform critical tasks. For example, they can tell when a bat detector has picked up a particular species, collect data from a tagged butterfly, or read a rain gauge.

One example of the power of citizen science is the Audubon Society's Christmas bird count. As the name suggests, around Christmas time, volunteers count the number of birds of different species in an assigned area. Teams might include people with various levels of expertise along with experienced birders. This has been an annual event for over a century. Christmas bird count data can answer questions such as whether populations of birds have increased in the decades after DDT was banned. One scientist studying a species in one place could never match the data set provided by the Christmas bird counts.

**Check Your Understanding**

- Give some examples of how people who do not have scientific degrees can help professional scientists.
- What are some other benefits of including non-scientists in scientific research?

# Key Concepts

- Ecology is the scientific study of relationships involving living and non-living things.
- The science framework is used to explore the world. Objective data are used to make and test hypotheses about how the world works. Explanations must conform to natural law.
- A relationship between variables is called a correlation. A correlation does not mean that one variable causes the other.
- A valid scientific experiment must be designed carefully to avoid bias and confounding variables. The sample must be large and representative.
- Anyone can do science if they use the science framework.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately apply the science framework to the study of ecology*
2. *Design valid experiments*
3. *Draw reasonable conclusions from scientific data*

1. Environmentalists work toward the protection of the environment. Are ecologists the same as environmentalists? Explain your answer. *(Learning Outcomes 1)*

2. Your friend reads a news story about an environmental study and says, “Everyone has an opinion about that and they’re all equally valid.” Explain what elements make an experiment scientifically valid and how that differs from an opinion. *(Learning Outcomes 1 and 2)*

3. We often hear people say things like, “I have a theory that I’ll get to campus faster if I take a different route.” Is this a theory in the scientific sense? Explain your answer. *(Learning Outcome 2)*

4. Your friend says she tested a hypothesis in her science lab and “proved it.” Is this possible? Explain your answer. *(Learning Outcome 2 and 3)*

5. Suppose you were looking for the cause of skin cancer and found a correlation between ice cream consumption and the number of skin cancer cases in different US cities (hypothetical data in Figure 17).

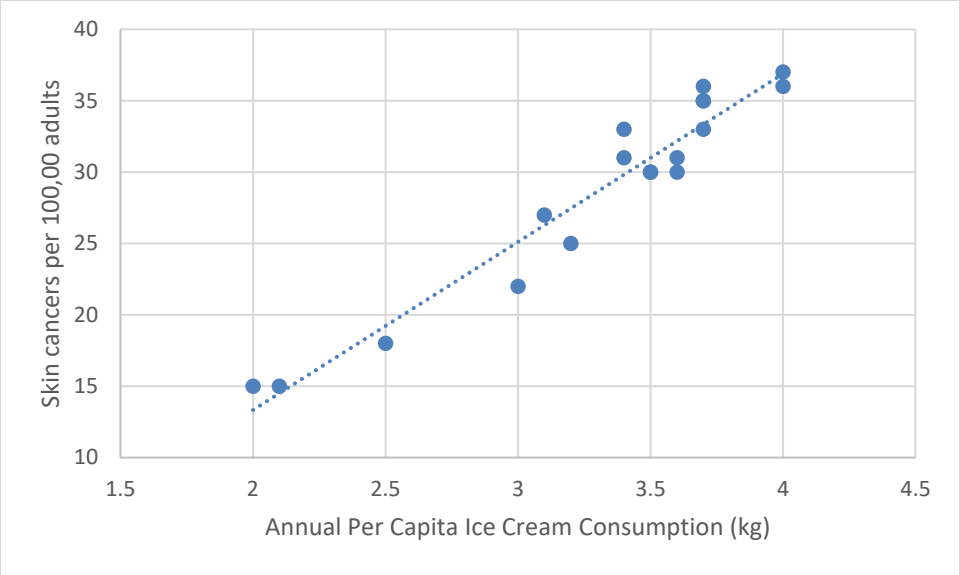



Figure 17. Hypothetical data on the relationship between ice cream consumption in various communities and cases of skin cancer. Each marker represents one community. The dotted line is a model showing the general trend of the relationship between the variables.

A. Which variable is the independent variable?
B. Which variable is the dependent variable?
C. Identify any potential confounding variables.
D. Does this data set provide convincing evidence that ice cream causes skin cancer? Explain your answer.

*(Learning Outcomes 2 and 3)*

6. Suppose you wanted to test the hypothesis that larger lakes had more species of fish.

A. How many lakes would you use? Why?
B. How would you choose which lakes to test?
C. Why is it important to have a protocol for how to measure lake size and number of fish species?

*(Learning Outcomes 2 and 3)*

# Chapter 2: How Ecology informs Environmental Decisions

### Case Study Part 1: Should the Dams Stay or Go?

https://www.fisheries.noaa.gov/feature-story/dam-removals-move-forward-noaa-explores-next-steps-habitat-restoration-klamath

Figure 1. Iron Gate Dam on the Klamath River in California in 2022. Below the dam the photo shows a power plant for turning the energy from water flow under the dam into electrical energy. A spillway on the left was used to send overflow downstream.

Should we be building more dams, maintaining the ones we have, or removing dams? Dams create artificial lakes—reservoirs—that do many things. They store water, providing a reliable supply to farms, ranches, households, and businesses. They help prevent small and seasonal floods. The flow of water below the dam can be used to produce electrical energy. People use the reservoirs for recreation, such as boating, fishing, and camping. Reservoirs may increase

nearby property values and support tourist industries. Water flow can be critical to many non-human species.

Dams also have negative effects. They stop fish like salmon from going up the river to reproduce. Some of the water in the reservoir evaporates, so it is not available downstream. The water below the dam is warmer. This can hurt fish and other aquatic species. Sediment—soil and other particles—settles in the reservoir. This reduces the nutrients and soil that would normally be delivered downstream. Dam failures are rare, but cause huge, destructive floods. Natural spring floods are prevented, which may hurt some species and lead to loss of beaches.

The Klamath River flows through Oregon and California. It is the center of a controversy about dams. The first dams were built there early in the 20th century. They created a series of reservoirs and were used to generate electrical power. They were also an important factor in the fight over water rights and fish conservation. The company that owned the dams wanted to transfer them to the federal government to avoid costs of upgrading and maintaining them. Others wanted the government to take on these responsibilities and keep the dams. Still others wanted the government to remove the dams and restore the Klamath River to a more natural state. Different sides presented a variety of ecological, economic, legal, cultural, and political evidence to make their arguments. Chapter 1 discussed how ecology might help an individual to make a personal decision. The story of Klamath River dams illustrates how society uses information from ecology and other frameworks to make public policy decisions that affect many people.

**Learning from the Case Study**

- What are some advantages and disadvantages of dams?
- If you were a public official, what *scientific* information would help you to decide whether to keep or remove a particular dam?
- Are there important questions about dam removal that science alone could not answer?

# Learning Outcomes

1. *Accurately analyze the role of science in making environmental decisions*
2. *Use the concept of sustainability to evaluate environmental decisions*
3. *Draw reasonable conclusions about how the stakeholders in environmental decisions influence resolutions and outcomes*
4. *Evaluate the quality of ecological evidence that might be used in environmental decisions*

**Vocabulary Toolkit**

**Opposites**
Sustainable and Unsustainable

**Word Watch List**
**Environmental science**: Field of study concerned with environmental issues and actions. Includes frameworks such as natural science, economics, behavioral science, and politics
**Sustainable**: Activity can be continued indefinitely; resource consumption does not exceed availability, production of wastes does not exceed disposal capacity
**Unsustainable**: Activity uses resources or produces wastes faster than can be supported.
**Stakeholders**: People with an interest (stake) in an issue. The interest is often economic, political, values-based, health-related, cultural, or aesthetic.
**Resolutions**: Action plans created to deal with environmental issues.
**Mitigation**: Actions taken to reduce a negative effect
**Translocation**: Moving individuals or populations, usually to allow other uses for their former habitat

## Many Factors Influence Environmental Decisions

Environmental decisions happen in your community all the time. They influence many actions, including land use, resource use, disposal of wastes, taxes, and even your health. Almost anyone can influence environmental decisions, whether they are giving input at a neighborhood planning session, voting, demonstrating, raising funds, or contacting elected officials. If you understand ecological concepts and their relationship with other frameworks, you will be able to increase your influence on issues that involve your community (see **Why It Matters: You Have a Voice**).

**Why It Matters: You Have a Voice**

*The world is run by those who show up.*

http://www.blm.gov/ca/st/en/info/newsbytes/2008/332-xtra_ccma_scoping.html

Figure 2. A stakeholder speaks to a US Bureau of Land Management official at a public meeting.

Understanding ecological concepts and environmental issues is important because citizens can influence decisions more than they think.

The National Environmental Policy Act of 1969 requires federal agencies to evaluate potential environmental impacts when planning a major federal action. The agencies must gather information, increase public awareness, and listen to the public. States and municipalities are also required to get citizen input on a variety of issues. You may be a stakeholder in local decisions about land use, endangered species, new construction, utility rates, freeway routing, bike lanes, water quality, or some other topic.

Agencies hold public meetings to give the public information about a proposed action, answer questions, and listen to concerns. Stakeholders who understand the science framework and ecological concepts are much more likely to understand the implications of proposed actions and to influence decisions that influence them.

- What factors determine a person's power to influence decisions on environmental issues?
- What environmental issues influence the quality of life in your own community?

**Misconception Alert: Science can tell people what they should do about environmental Issues**

**FALSE.** Science can only provide factual information, predictions, and explanations. What anyone should do with these tools is subjective. Ecologists may be able to predict that a certain species will probably go extinct if its habitat is destroyed. They may be able to predict the effect on other species in the ecosystem. People must decide what to do with the information. Two people with the same level of scientific thinking ability and the same set of data may have very different opinions about appropriate actions. Their interests and values will probably guide their decisions.

**Environmental science** is the study of actions and policies that influence Earth and its ecosystems. It combines input from various fields to understand environmental issues and help make reasonable plans. Ecology provides information about ecosystems; their current state, inferences about their past condition, and predictions about how they may change. Ecology helps decision-makers understand how biotic and abiotic systems work, how they adapt, and limits to their adaptation (see **Evolutionary Perspectives: Natural Selection and Management Decisions**). Other natural sciences, such as physics, chemistry, and genetics also provide information for the understanding the effects of human activity on the environment.

**Evolutionary Perspectives: Natural Selection and Management Decisions**

Good management decisions require a solid understanding of evolutionary concepts. Many people wrongly believe that species will get genetic adaptations to environmental changes just because they need to. For example, they may believe that a hotter or drier climate will cause mutations for tolerating these conditions. Mutations do not happen due to needing them or trying to get them. *Mutations are random events*. Environmental factors such as radiation and certain chemicals can increase mutation *rates*, but the mutations are still random. Chapter 4 will discuss this in more detail.

Natural selection is *not* random. If an individual happens to have a gene that helps it live in the changed environment, that individual will probably leave more offspring than other individuals in the population, making that gene more common in future generation. But this will not happen unless a *random* mutation produces that variety of gene.

Effective management of species depends on understanding the limits of natural selection. Counting on natural selection to “fix” species so that they can overcome new environmental challenges is not a valid strategy, it is wishful thinking.

Almost every field of knowledge can be useful in exploring at least some environmental issues. Understanding values and what motivates people to behave in certain ways is essential for good environmental decisions (Figure 3). Fields such as ethics, art, history, philosophy, religious studies, psychology, and sociology can help to identify and answer important questions about human values and behavior. This will be explored more in Chapter 19. Economics and business

also have a major influence on environmental decisions, helping to identify costs, changes in pricing, business growth, employment, and other issues involving money. Medical information is important when environmental actions will influence people's health. Effectively implementing decisions requires a solid understanding of politics, law, public relations, education, engineering, and other fields. Environmental science combines all these frameworks. Apply this concept with environmental issues that influence your life with **Do Try this at Home: Analyzing Local Issues**.

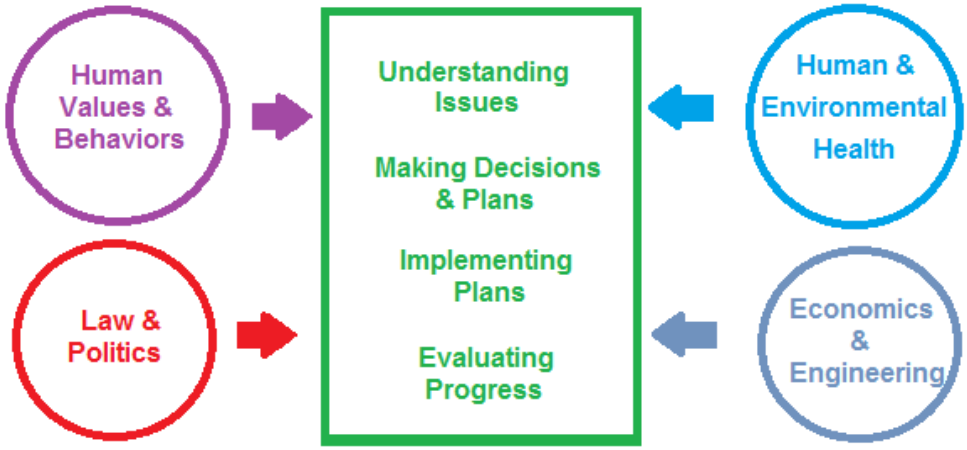



Figure 3. Visual model for the interaction of some elements involved in understanding and dealing with environmental issues.

**Check Your Understanding**

- What kinds of information can ecology provide?
- What other types of information are critical to making environmental decisions?

**Do Try this at Home: Analyzing Local Issues**

Use a local news source to identify an environmental issue in your area. Try to identify as many stakeholders as possible. Who has particular opinions on the issue? What seem to be behind their opinions (values, self-interest, economic necessity, etc.)? Do all of the stakeholders seem to have similar power in the process? What are the scientific facts? Does everyone agree on them?

**Sustainable Practices Can Continue Indefinitely**

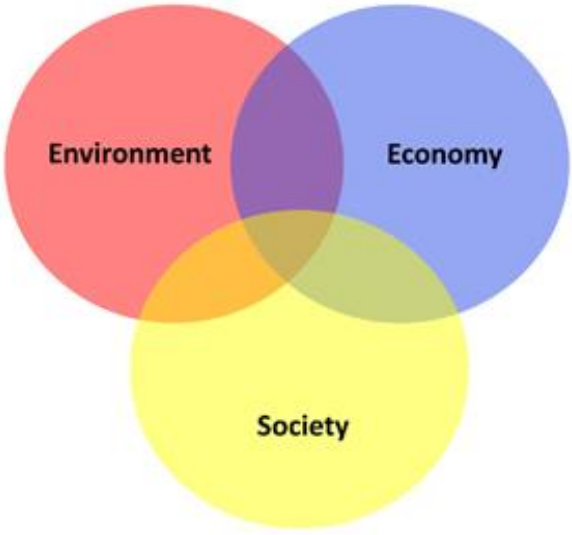
Can we continue to use fossil fuels (e.g. coal, oil, and gas) at our current rate? Can we safely store radioactive materials that will remain dangerous for tens of thousands of years? Can we allow trophy hunting of grizzly bears without causing their extinction? These are all questions about **sustainability**. When we ask whether a practice is sustainable, we are asking whether we can continue an action indefinitely, or at least for a long time. If a practice uses resources

faster than they can be replaced, or produces waste faster than it can be safely disposed of, it is **unsustainable**.

If you spend more than you earn, your spending is unsustainable. You might use credit cards or other types of loans for a while, but this will only make your debt greater. In the same way, we can use fossil fuels much faster than they form. We can even develop technology to find and get more of the remaining fossil fuels, but these resources will eventually run out.

We can measure environmental sustainability using the science framework. This usually involves models about current usage, predictions about how usage will change (due to population size, alternatives, cost, regulations, education, etc.) and whether availability of resources or ability to dispose of wastes will change (due to changing technology, cost, regulations, etc.). Models require assumptions and estimates, so people may disagree about how realistic specific models are. Even if people agree on similar models, they may have different opinions on what should be done.

Environmental science deals with economic and social sustainability as well as environmental sustainability (Figure 4). If a plan is sustainable in all three domains, it is much more likely to succeed. A plan that is good for people and the environment but is not economically feasible has a low chance for long-term success. A plan that is profitable and benefits the people involved but uses natural resources too quickly is not sustainable. A plan that is economically profitable and good for the environment but is unfair to the people involved will probably not get the local support it needs.




http://www.epa.gov/region4/p2/sustainability.html

Figure 4. Three domains of sustainability. Plans that are sustainable in all three domains usually have the highest probability of success. To understand the logic of the diagram, see **Model Skill: Venn Diagrams**.

**Analyze the Figure**

- What does it mean if something is only in the society circle?
- What does it mean if something is in the purple area where environment and economy intersect?

**Model Skill: Venn Diagrams**

**Venn diagrams** are visual models that show sets. For example, suppose that you wanted to show the relationship between domestic and wild animals. If you assume that there is no overlap between the groups, you would have two separate circles. You would put domestic animals in one and wild animals in the other (Figure 5).

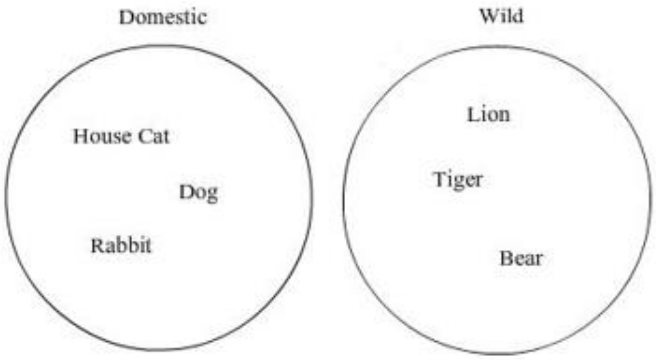



Figure 5. A Venn diagram showing no overlap between some wild and domestic animals.

Perhaps you remembered seeing wild rabbits as well as pet ones. Then you would show that rabbits belong to both groups by overlapping the groups and putting rabbits in the area where the two circles overlap (Figure 6). Rabbits would then be in the intersection of domestic and wild animals.

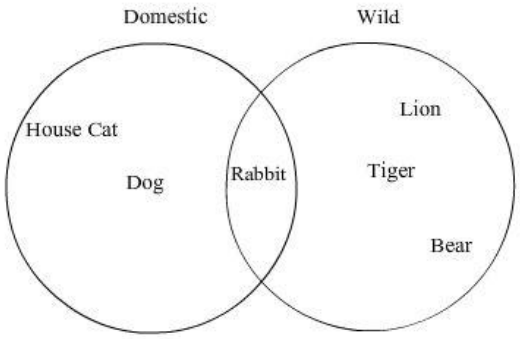



Figure 6. A Venn diagram showing overlap between wild and domestic animals.

**Continued**

**Model Skill: Venn Diagrams, cont.**

All the animals in the diagram are mammals, so you could show this by putting both the circles within a larger shape (Figure 7). Obviously, there are many more mammals in the world than there are in this diagram, but the box is called the universal set because it contains all of the mammals we are interested in at this time.

Venn diagrams can be used to show complex relationships, but the underlying logic is simple: items are shown as either belonging to a set (inside the shape) or not. An item can belong to multiple sets. An entire set can be a part of a larger set.

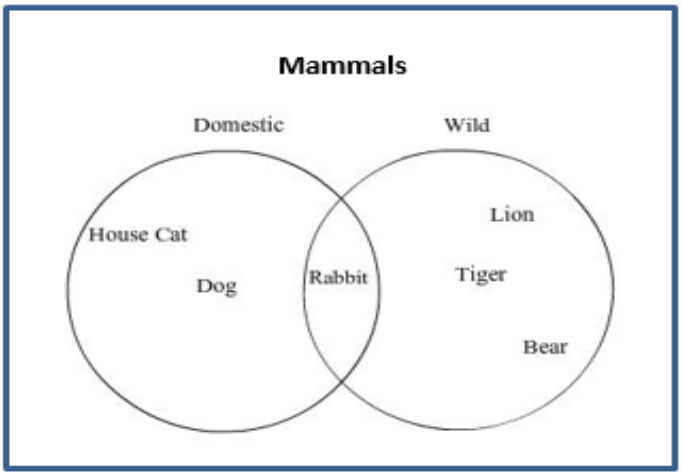



Figure 7. Venn diagram showing that all the animals in the diagram are mammals.

**Case Study Part 2: Is Klamath River Water Use Sustainable?**

**A**

https://itoldya420.getarchive.net/amp/media/irrigation-canal-outside-klamath-falls-oregon-9d767e

**B**

http://www.fs.usda.gov/detail/klamath/landmanagement/resourcemanagement/?cid=stelprdb5121663

Figure 8. **A**. Irrigation canal in the Klamath Basin. **B**. US Forest Service biologists count salmon in streams that lead to the Klamath River.

The Klamath River depends on snow melt from the mountains. The areas it flows through do not receive a lot of rain. Farmers and ranchers use irrigation water to make up the difference between their needs and what local rain and snow provide. When power companies built dams along the Klamath River, they made a deal with the farmers and ranchers who already had claims on the water. The power company agreed to provide electrical power at a very low rate for 50 years. The farmers and ranchers agreed to send water back to the Klamath River and reservoirs. Of course, much of the water was used or lost, but the rest was returned. Other people who depended on the river—such as indigenous people—had little input.

During dry years, there was not enough water for both irrigation and maintaining enough water in the river to keep fish alive. The Klamath Tribes lost a valuable resource when they could no longer catch salmon. In 2001, the Endangered Species Act was used to divert water to the river to save 3 species of fish. Farmers and ranchers could not get irrigation water and lost tens of millions of dollars. In 2002, water was diverted to irrigation, and there was a large fish die-off. This “Fish vs. Farm” controversy is a good example of the different types of sustainability. Environmentally, there is not enough water to give both sides as much as they want during drought years. Both the people who use water for irrigation and the native people of the Klamath Tribes who value fish believe that they have a more important claim on the water. Both sides have economic losses when they do not get enough water for their purposes. For more discussion on how public resources such as water are used and misused, see **Taking It Further: The Tragedy of the Commons**.

**Learning from the Case Study**

- If water is managed so that native fish populations are healthy what economic and social costs might there be?

- If water is managed so that farms and ranches get all the water they demand, what economic and social costs might there be?
- Is there any way for the water use to be sustainable in all three dimensions (environmental, social, and economic)?

**Taking It Further: The Tragedy of the Commons**

As populations grow, practices that were sustainable can become unsustainable. For example, most modern cities once dumped their raw sewage and other wastes directly into rivers. As populations grew, rivers became so polluted that they offended even people who did not understand that germs cause disease. When hunters were rare, they could sustainably hunt as many animals as they needed. As numbers of hunters grew, game regulations were needed to keep game animals from disappearing.

In the 1960s, population growth became a controversial issue. If Earth's population continued to grow faster and faster, could enough food, water, and other resources be found? What would happen with all of the waste? Some people maintained that technology would solve these problems. Garrett Hardin wrote a famous article contending that the problems of overpopulation could not be solved by technology because the issue was really a moral one. Hardin's story of the Tragedy of the Commons continues to influence the discussion of how self-interest leads people to treat community-owned assets differently than the assets they own privately.

Hardin asked readers to imagine a pasture that belonged to an entire community. Each person could graze livestock there. If the number of people and their livestock remain low, this is a sustainable practice. But when the numbers increase too much, animals will eat so much that the pasture is worthless. A wise farmer will not put too many animals on a private field because using the private resource sustainably maintains a valuable resource. But the farmer may think "just a few more won't hurt" when putting animals on the community field. Having more animals serves the farmer's private interest. The gain from the extra animals goes to the owner. The cost of the extra animals is shared by all. When all farmers do the same thing, the pasture is destroyed by unsustainably high grazing levels. The shared benefit of long-term sustainability may not be enough to prevent individuals from trying to get selfish short-term gain.

This same thinking can apply to waste disposal. It is unlikely that an owner would dump her household waste into her own fish pond. It would go against her self-interest. If several people own cabins by a public fishing lake, some owners may dump waste into the lake to avoid the expense of non-polluting waste systems. The person's self-interest (saving money) may be more important to them than sustainable use of a public resource (the lake).

**Check Your Understanding**

- What does "sustainable" mean?
- How might an action be environmentally sustainable, but not economically or societally sustainable?

**Stakeholders may Compromise to Resolve Issues**

The people and organizations influenced by a particular decision are called **stakeholders** because they have a stake or interest in what happens. For example, suppose that planners wanted to make a city freeway safer. Stakeholders would include drivers who use the freeway and those whose homes, businesses, or commuting routes are near the freeway. Businesses might be helped or hurt by changing traffic patterns, making all of those involved in the businesses (owners, employees, stockholders, and customers) potential stakeholders. People and organizations concerned with the impact on wildlife, historical buildings, and cultural assets would be stakeholders as well. Taxpayers would have an economic stake in the decision, even if they never visit that area of the city.

If an action may cause environmental damage, disruption to human communities, or other negative effects, stakeholders may consider **mitigation** plans that are intended to reduce the harm of an activity. Mitigations allow some flexibility in plans. For example, construction can cause traffic problems. A developer might guarantee certain steps that would reduce construction traffic, such as working during non-peak traffic hours, or using different routes for construction equipment. For an example of a mitigation plan, see **Hypothesis Testing: Can Translocations Be More Effective?**

With so many stakeholders and competing interests, it is unlikely that any plan is going to completely satisfy everyone. Decision makers usually try to balance the needs of various stakeholders and the different domains of sustainability to find the best plan (or at least one that is the least unpopular). Some stakeholders may have a lot more influence over the decisions. The federal government offers some protections to help keep people with less political power from being unfairly exposed to more environmental health risks (see **Make the Medical Connection: Environmental Justice and Community Health**). Final plans are often called **resolutions** because stakeholders unsatisfied with the plans might not consider them solutions.

**Hypothesis Testing: Can Translocations Be More Effective?**

Regulations limit development that would harm protected species. Developers often propose **translocating** (moving) individuals of the protected species to mitigate the impact of the development. This may seem like a reasonable solution that benefits the developers and the protected species. Unfortunately, most mitigation-driven translocations are not monitored to evaluate their success. There are reasons to question whether translocations are a viable mitigation strategy. If the destination habitat is suitable, why isn't it already inhabited by the species? If the destination habitat is already inhabited by the species, will additional individuals increase the population size above a sustainable level? Will translocations disrupt the behavior of animals? Do translocations just move populations to an area where their deaths will not be as obvious?

Stephens' kangaroo rats (Figure 9) are endangered. They have been subjected to several mitigation-driven translocation efforts as residential developments spread in the area between Los Angeles and San Diego in California. Until 2011, none of these translocations had resulted in any documented cases of surviving translocated kangaroo rats one year after the translocation.

https://www.fws.gov/species/stephens-kangaroo-rat-dipodomys-stephensi

Figure 9. Stephen's kangaroo rat (*Dipodomys stephenis*), a small mammal that lives in solitary dens in southwestern California.

Kangaroo rats live in solitary burrows, but they are part of a "neighborhood" of familiar individuals that communicate with each other by drumming on the ground with their feet. Familiar neighbors spend little time and energy interacting once boundaries have been established, but strangers disrupt the neighborhood, causing much more time and energy to be spent on displays or actual fighting. This is consistent with what studies on many species have shown—the "dear enemy" effect.

A kangaroo rat released in a new area would have to look for a new burrow site, fight with new neighbors, and dig a new burrow. Fighting takes time and energy. The translocated animal might be injured while fighting and would have less time to forage for food. Burrows protect kangaroo rats from the hot, dry environment and from predators. Exposed kangaroo rats would

experience more stress and danger. Burrows also store food for times when food is scarce. A kangaroo rat would have to collect a lot of food to store.

Shier and Swaisgood (2012) studied whether the success of relocations could be improved by adapting the relocation plan to the behavior of a species.

Hypothesis: Social disruption causes low survival in translocated Stephens' kangaroo rats.

Their hypothesis led to the following predictions about Stephens' kangaroo rats translocated with neighbors (compared to those being translocated as individuals):

- A higher survival rate
- Less travel before establishing a new home
- Faster settlement into burrows
- Less time fighting
- More time foraging
- Increased long term reproduction

The researchers spent many hours identifying individuals and mapping their locations. Small transmitters were attached to the animals, and they were transported to their relocation site. The release site had the correct type of soil and was prepared for the translocated animals by managing the vegetation. When each animal arrived at the new site, it was held in a translocation cage that extended above and below the ground. The purpose was to increase the probability that each animal would get used to its new site and stay in that location. The site as a whole was also protected by a coyote-proof fence. One set of kangaroo rats was placed in approximately the same relative positions they had had in the original site. The other set did not include close neighbors and individuals were placed in random locations, but with spacing similar to that of the group moved with neighbors. The researchers then studied behavior, survival, and reproduction of the translocated animals (Figures 10 & 11).

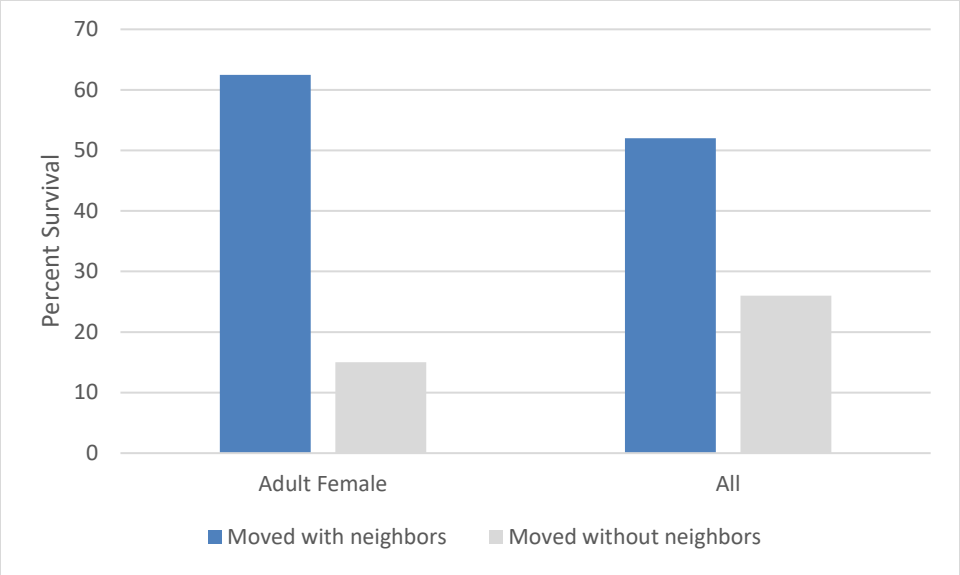



Figure 10. Survival of Stephens' kangaroo rats 6 months after relocation when translocated with and without their neighbors. Based on data from: Shier, D. M., & Swaisgood, R. R. (2012). Fitness costs of neighborhood disruption in translocations of a solitary mammal. *Conservation Biology*,*26*(1), 116-123.

**Analyze the Figure**

- Which kangaroo rats had a higher survival rate, those translocated with neighbors or those translocated without neighbors?
- Did being translocated with neighbors have a greater effect on 6-month survival of adult females than on the population overall?

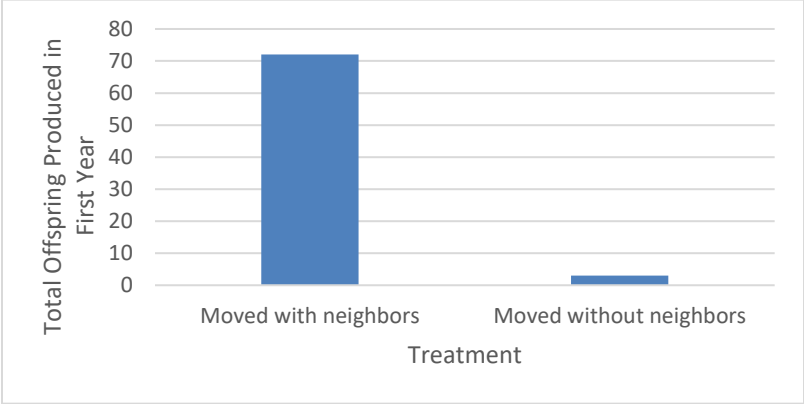



Figure 11. Reproductive success of Stephens' kangaroo rat population in first year when translocated with and without neighbors. Based on data from: Shier, D. M., & Swaisgood, R. R. (2012). Fitness costs of neighborhood disruption in translocations of a solitary mammal. *Conservation Biology*,*26*(1), 116-123.

**Analyze the Figure**

- What was the effect of being translocated with neighbors on reproductive success of the kangaroo rats?

The kangaroo rats translocated with their neighbors also tended to settle faster and have fewer fights when moved with their neighbors. They spent more time foraging for food and dug more burrows.

**Evaluate the Hypothesis**

- Which predictions were matched by the data?
- Do the data support the hypothesis that social disruption was responsible for some of the deaths of translocated kangaroo rats?
- Do the data support a hypothesis that social disruption was responsible for all the deaths of translocated kangaroo rats? What additional information would help you to evaluate that hypothesis?

**Make the Medical Connection: Environmental Justice and Community Health**

https://factor.niehs.nih.gov/2023/11/feature/NIH-environmental-justice

Should a person's income level or ethnicity determine whether environmental health hazards are placed in their community? Proponents of environmental justice began fighting for justice in environmental policy in the late 1970s and early 1980s. They noted that environmental health hazards were more common in low-income areas and areas with higher proportions of non-white residents. The pattern may have been the result of overt discrimination, confounding factors (such as cheap land, lack of political power and connections), or a combination of causes.

On February 11, 1994, President Clinton signed an executive order that directed US federal agencies to identify low income and minority communities that had been disproportionately burdened by environmental hazards. Agencies were also directed to begin fixing these problems as much as they could and to increase the involvement of low-income and minority groups in environmental decisions that impact their communities.

The National Institutes of Health (NIH) Environmental Justice Working Group is tasked with implementing policies that promote environmental justice, both in the US and internationally.

**Case Study Part 3: Who are the Klamath River Stakeholders?**

https://en.wikipedia.org/wiki/Un-Dam_the_Klamath#/media/File:Klamath_tribes_dam_removal_demo.jpg

Figure 12. Stakeholders demonstrating for removal of the Klamath River Dams.

Many people have an interest in the fate of dams on the Klamath River and elsewhere. As mentioned in Part 2, farmers and ranchers need irrigation water to stay in business. People who fish—including Klamath Tribal members—need water flow to keep fish alive. There are many other stakeholders. Households and businesses want affordable, dependable water supplies. The local tourist industry depends on recreation opportunities such as boating and fishing. Homeowners may see major changes in their property value if the reservoir near their home disappears.

In the western United States, the highest priority for water use depends on who has been using the water for "beneficial" purposes the longest. Farmers and ranchers were recognized as senior users for decades. Native people won a major victory when they were recognized as the senior users of the Upper Klamath Basin water in 2013. This potentially allowed them to have water cut off to more junior water users when demand was greater than supply.

Although interactions between the groups have not always been friendly, the major stakeholders developed agreements attempting to balance the needs of the people who use irrigation with the needs of the people who rely on healthy fish populations. The resolution included removing the four major dams that block salmon from migrating upstream. The Klamath Tribes agreed to share water with irrigators in exchange for conservation actions and money that can be used to help with employment and other social needs. In 2022, decisions were finalized. Dam removal began in August of 2024.

**Learning from the Case Study**

- Who are some of the stakeholders in the dam removal controversy?

- Why is it unlikely that any resolution could satisfy all the stakeholders equally?
- Which stakeholders do you think might have more power to influence the decision? Explain the source of the power.

**Check Your Understanding**

- What are stakeholders?
- How might various frameworks (e.g. economics, social science, environmental science) be useful for understanding the different positions of stakeholders?

**Good Decisions Require Valid Data**

Any citizen trying to use scientific data to decide which public policies they support must ask "what do the data say?" and "how good are the data?" Recall from Chapter 1 that data are only as good as the method used to collect them. Stakeholders sometimes allow their own interests to influence how they collect or interpret data. When evaluating data, keep the following questions in mind:

- Was the sample large enough? Larger samples are better. The more variation there is in the data, the bigger the sample should be.

- Who conducted or paid for the study? Studies conducted or funded by independent agencies may be more credible.

- Was the sample representative? If a study claims something about the population of your state, everyone in your state should have an equal chance to be included. This is often not possible, but some samples are more representative than others. A survey conducted at a boat ramp is likely to include more people who want more boat docks than a survey taken at a jazz concert. If the study is comparing data from two dates, are those dates representative of a general trend, or are they unusually high or low values?

- Was this an experiment or a comparison? Were people, lakes, mushrooms or other units put into different groups randomly, then treated the same except for one variable? Or were data collected on units that were already in different groups (people living near landfills or not, lakes on the north or south side of a slope, or mushrooms under trees or not)? A controlled experiment is much better evidence that a variable caused a pattern, but it might not be possible for ethical, economic, or other reasons.

- Did the sample cover enough space or time? Some things take a while to happen. A study that shows no increase in cancer a year after a toxic spill is not as convincing as one that follows people for decades. Are hummingbird populations decreasing? Data from the entire US are more convincing than data from one county.

- Are the differences between groups statistically significant? This tells you that the difference is not very likely to be due to background variation in the data sets. Statistical significance does not tell you whether the difference is important. That is a subjective judgment. If people exposed to a toxin had a 1% higher chance of cancer or lived one day less, is that important? There is no scientific answer to that question. (Appendix D has advice on reading specific types of graphs. Appendix C provides information on specific statistical tests.)

- Are the sources cited from scientific, peer-reviewed journals (see **Taking It Further: Peer Review** in Chapter 1)? These sources carry a lot more credibility than other sources. You may need to look up the actual papers cited. Sometimes the data reported in popular news outlets are not the data in the original technical papers.

- Are the results of the current study published in a scientific, peer-reviewed journal? This adds greatly to the credibility of a study. It does take some time for papers to be published, so a study that was just concluded would not be published yet. It is fairly easy to make a web site look like a source of valid, technical information, so in the digital age, you may need to do some research on whether the journal is reputable.

Effectively evaluating data and models will help you understand the complicated environmental issues that face Earth and your own community.

**Check Your Understanding:**

- Why is a large sample size important?
- How could data be correct, but not represent an actual trend? Give an example.

# Key Concepts

- Ecology provides scientific information about environmental issues. Other frameworks are also essential for understanding issues and action.
- Sustainable practices can continue indefinitely because they do not use resources faster than they are created or create wastes faster than they can be safely eliminated.
- Environmental issues usually have many stakeholders with different interests and levels of power to influence decisions.
- Non-scientists can participate in environmental decision making.

# Apply the Concepts

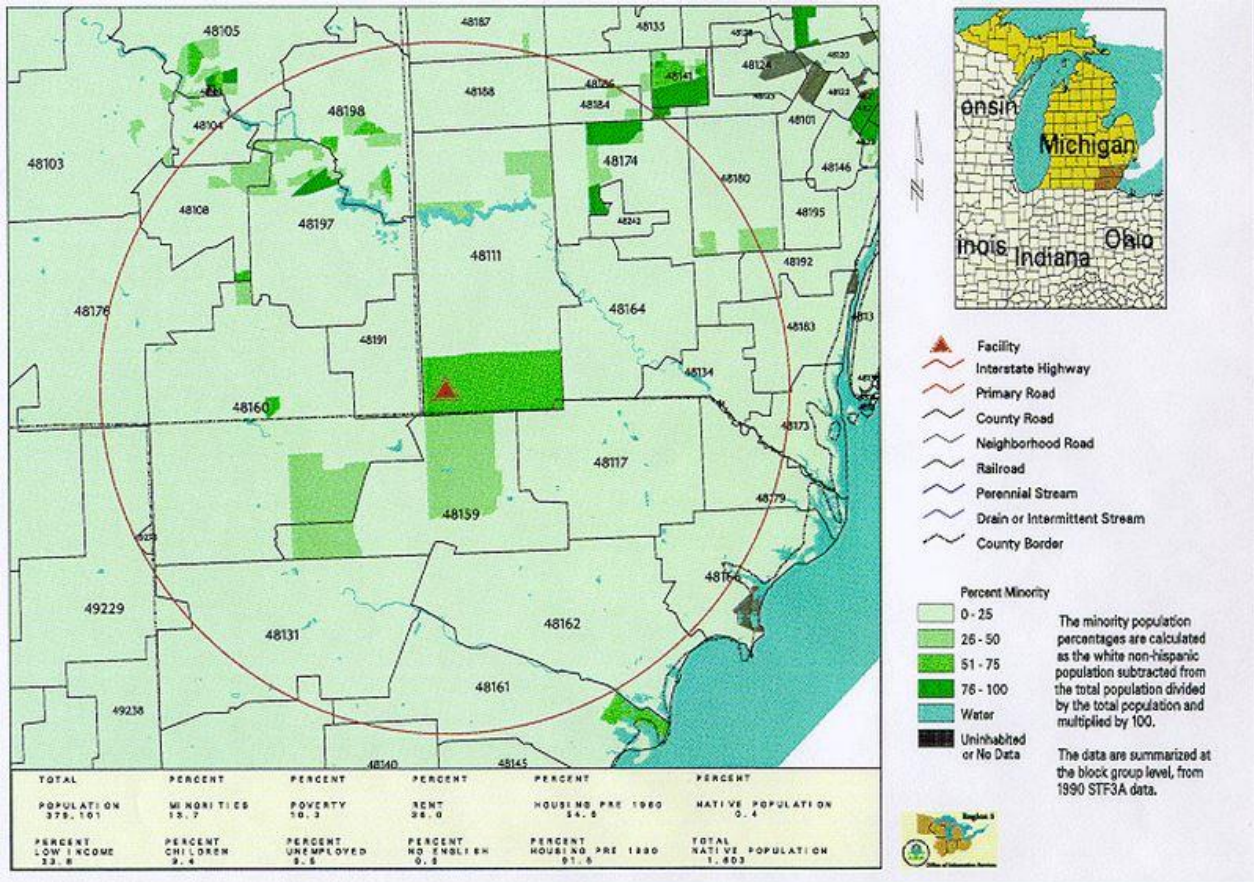
**Learning Outcomes**

1. *Accurately analyze the role of science in making environmental decisions*
2. *Use the concept of sustainability to evaluate environmental decisions*
3. *Draw reasonable conclusions about how the stakeholders in environmental decisions influence resolutions and outcomes*
4. *Evaluate the quality of ecological evidence that might be used in environmental decisions*

1. Check a local news source to identify an environmental issue.
    A. What ecological information is needed to answer this question?
    B. What information or perspectives might be needed from other frameworks (e.g. behavioral science, history, law, economics, politics, culture, etc.)?
    C. Is the concept of sustainability useful in understanding this issue? Explain your answer.
    *(Learning Outcomes 1, 2, and 3)*

2. Imagine that a city wanted to avoid flooding by buying all of houses along a part of a river and making a flood-control area.
    A. Identify some of the stakeholders.
    B. Identify how the three domains (environment, people, and economics) are all involved in the issue, giving an example of an important factor in each.
    C. Which stakeholders (or groups) do you think would have the most influence on the final resolution? Explain your reasoning.
    *(Learning Outcome 3)*

3. In 1991, the Envotech company requested permits to drill two wells in Washtenaw County, MI for disposing of hazardous waste from landfills and a proposed incinerator. The US EPA granted the permits in 1995. As part of the appeals process, people opposed to the wells claimed that this was an environmental justice issue. They submitted demographic maps, including one showing high levels of minority population in the proposed area (Figure 13). The appeals were denied in 1996 and final permits were issued.




http://www.epa.gov/r5water/uic/ej/

Figure 13. Proposed site for the wells (red triangle) and the 15-mile radius around it (red circle). Minority demographics are shown in green. The area surrounding the proposed site shows ethnic minority levels as 51-75% of the population.

A. How might different stakeholders have had different levels of power in this decision?
B. What factors may have led to the final resolution?
*(Learning Outcome 3)*

4. Suppose that you wanted to find out whether a waste site caused health problems for people nearby.

A. How would you study the question to get the most accurate answer?
B. What limitations would there be on how you could study it (logistical, ethical, legal, etc.)?
C. Which would be a reliable source of data from other studies: Newspaper article, report by a political action organization or waste disposal industry, article from a peer-reviewed, scientific journal? Explain your answer.
*(Learning Outcome 4)*

5. Consider the following list of questions and decide whether answering the question requires only the science framework, only a non-science framework (such as ethics, religion, aesthetics, or law) or both. Complete a Venn diagram (Figure 14) showing the set(s) for each question. Just use the letter rather than trying to write the entire question. Pay close attention to what the question is asking. For example, there is no way to scientifically test whether chocolate tastes better than vanilla. You could conduct a scientific survey about which flavor people prefer, but that is a different question; "tastes better" is a subjective judgment. *(Learning Outcome 1)*

   A. Are there more trees in my state now than there were in 1900?
   B. Are spotted owls worth saving?
   C. How many landfills are located in my state?
   D. Will there be enough energy available in 20 years to support a comfortable lifestyle?
   E. Do all people in my city have fair access to recreational areas?
   F. Are pine trees prettier than oak trees?

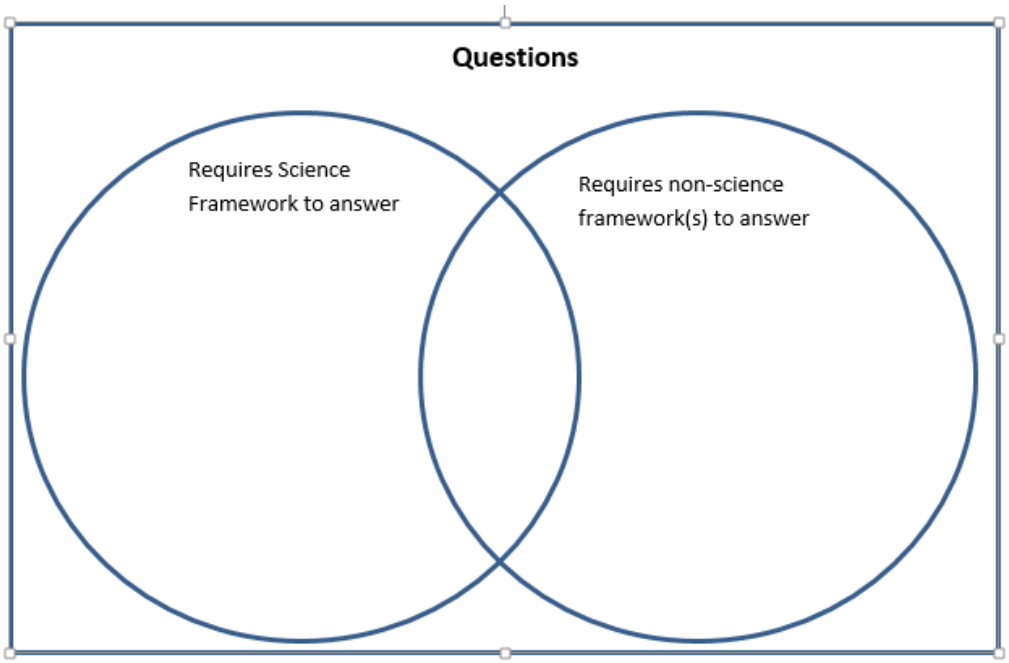



Figure 14. Incomplete Venn diagram.

# Chapter 3: Matter and Energy

**Case Study Part 1: There Is No "Away"**

https://www.epa.gov/eg/landfills-effluent-guidelines

Figure 1. A landfill. Earthmoving equipment compacts the waste and covers it with soil.

When you throw something away, where does it go? The specific answer depends a lot on where you live, but it always goes somewhere. People pile garbage up, bury it underground, burn it, or dump it in the ocean. Toxins from trash poison land and water. Some communities are running out of space for storing and processing their trash and send it elsewhere. This chapter will explore matter and energy, how they change, and whether they can ever disappear.

**Learning from the Case Study**

- Why is trash a problem?
- Is it likely that this problem will get better or worse?

# Learning Outcomes

1. *Clearly explain how matter is conserved and transformed.*
2. *Make valid predictions about how changes in heat will lead to changes in states and density of matter.*
3. *Clearly explain how energy is conserved, transformed, and dissipated.*
4. *Accurately identify functions of key molecules found in living organisms.*
5. *Clearly describe how energy and matter move through ecosystems.*

**Vocabulary Toolkit**

**Opposites**
Evaporation and Condensation

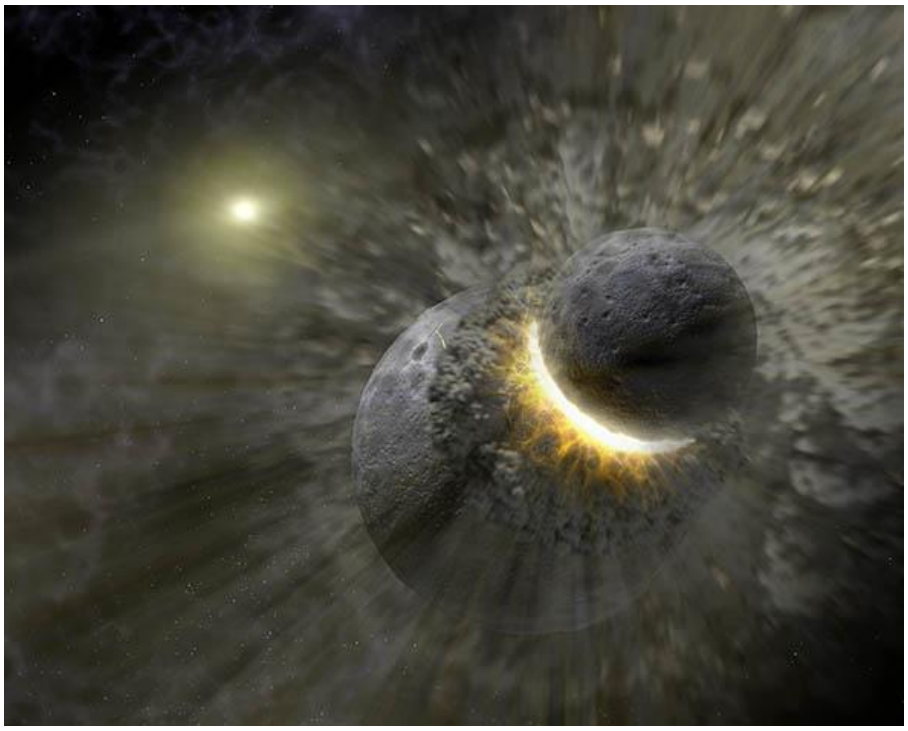
**Word Watch List**
**Matter**: Material that has mass and takes up space
**Evaporation**: Change from liquid state to gas state
**Condensation**: Change from gas state to liquid state
**Thermal inertia**: Property of maintaining temperature
**Density**: Mass divided by volume
**Energy**: Ability to do work
**Photosynthesis**: Process used by plants and other producers, using energy from the sun to turn carbon dioxide and water into sugar and oxygen
**Entropy**: Tendency for systems to go from order to disorder. Loss of energy as energy changes
**Potential energy**: Energy stored chemically, by position, or mechanically
**Kinetic energy**: Movement, including light, heat, and sound
**Greenhouse Gases**: Gases that increase the thickness of Earth's atmosphere, trapping heat and contributing to global climate change

**Matter cannot be created nor destroyed**

The movements of energy and matter through ecosystems are central to the study of ecology. Look around you. Everything you see is made of **matter**. Even the air around you is matter. It takes up space (meaning that it has volume) and it has mass. We commonly measure mass indirectly by weighing things.

Look at an object, such as a pen or coffee mug. Did it just appear from nothing, or was it made from materials that already existed? Can you make it go away? You can break the object, but you can't make the pieces stop existing. Whether it's a coffee cup or a planet, smashing objects into smaller pieces does not make them disappear (Figure 2). Matter has to come from

somewhere and go somewhere. This is part of the first law of thermodynamics: Matter can neither be created nor destroyed, it can only be transformed. The matter on earth may change forms many times as it passes through living and non-living systems, but the basic materials are not lost, and they don't just appear from nothing.



https://exoplanets.nasa.gov/resources/26/massive-smash-up-at-vega/

Figure 2. You can smash matter into smaller pieces, but it will still exist.

All the matter in our bodies has been circulating through the universe for billions of years. The unique organization of molecules into our bodies makes us who we are. Even after we die, our matter will continue to circulate through living and non-living objects for longer than we can imagine.

The only way to make matter "disappear" is to transform it into energy. This happens in nuclear reactions. Living things have no way to do this. In ecology, it is useful to think of energy and matter as being very different.

**Check Your Understanding**

- Is it possible to decrease the amount of matter on Earth? Explain your reasoning.
- Would a container full of air weigh more than a container with nothing in it? Explain your reasoning.
- Give your own example of changing one form of matter to another.

**Matter Can Change States**

Water molecules are critical for life on Earth. All living things we know of need water for their chemical reactions. They get and lose their water in a variety of ways. Water also moves through the non-living environment. We may see it as flowing rivers, clouds in the sky, falling rain, vast oceans, or in other forms (Figure 3).

Burton, 2005

Figure 3. Water is critical to life on Earth. It can be in many forms.

A water molecule contains two hydrogen atoms and an oxygen atom ($H_2O$, Figure 4). Oxygen and hydrogen have different properties. When they form a water molecule, the water molecule has its own properties.

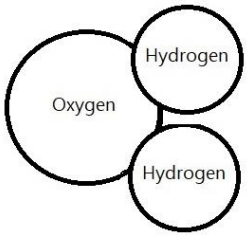
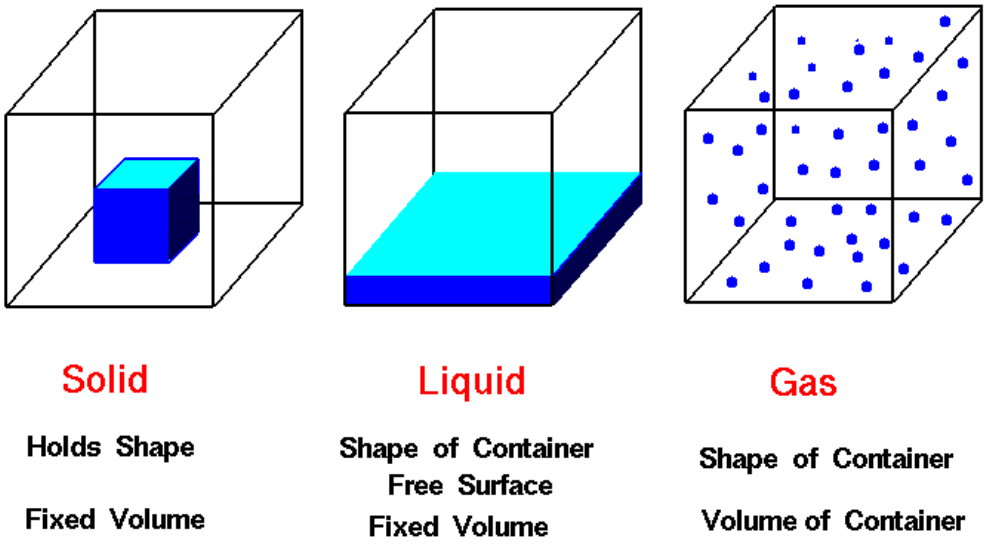



Figure 4. One way to represent a water molecule.

Even though the water molecule is always $H_2O$, water can be a liquid, a solid (ice), or a gas (water vapor; Figure 5). The difference between these states of water is in how much the water molecules are moving. In a solid, molecules vibrate, but don't switch places. Solids keep their shape, even if they are not in a container. In the liquid state, the molecules move around, changing places and bumping into each other. Liquids will take the shape of a container. In a

gas, the molecules move even more and are much farther apart. These Gases can be compressed to fit into a smaller container, meaning that their volume varies with pressure.




http://exploration.grc.nasa.gov/education/rocket/state.html

Figure 5. States of matter and their properties. Molecules are not visible, but are represented by dots in the diagram of gas. All have mass. The mass does not change with volume, but the density does.

**Analyze the Figure**

- Which state of matter holds its shape without a container?
- Which state of matter can be compressed (forced into a smaller volume)?
- Assume that you have the same amount of water in a liquid state and a gas state. Which one will have a larger volume (take up more space)?

**Misconception Alert: Gas has no mass.**

**FALSE.** Gases are matter and have mass. They are made of the same molecules as liquids and solids, the molecules are just farther apart. Think about blowing air into a balloon. Once you have tied the balloon off, you can't squash it flat because it contains matter. Air doesn't weigh very much compared to liquids and solids because it has a lower density. The mass is spread out into a greater volume. Demonstrate this to yourself using **Do Try this at Home: Gas has mass**.

**Do Try this at Home: Gas has mass**

What you will need:

- Two empty plastic screw-top bottles
- One or two caps for the bottles.
- One scale (if you don't have one, build a simple one: http://kriegerscience.wordpress.com/2011/09/28/how-to-make-a-set-of-weighing-scales/).
- Baking soda, 4 teaspoons
- Vinegar, 1 cup

Put two teaspoons or 10 mls or grams of baking soda into the bottom of each bottle. Make sure that you put the same amount in each bottle. Add ½ cup or 120 ml of vinegar to each bottle. Quickly cap one, but leave the cap off the other one. Put the bottles on opposite sides of your pan balance or wait until they are done fizzing, then weigh each of them. Remember to add the weight of the cap to the bottle that is not capped.

How does this demonstrate that gas has mass?

If you wanted to change a piece of ice from a solid to a liquid, what would you do? You would add heat to melt the ice. If you left this water uncovered, some of it would **evaporate** and become water vapor. Heat transforms matter between these states. When water vapor cools, some of the water will go from the gas state to the liquid state. This is called **condensation**. When warm wet air hits a cold glass, water vapor in the air condenses on the glass. When water cools enough, it freezes into ice. Water has a high **thermal inertia**, meaning that it takes it a long time to heat or cool compared to air, for example. All kinds of matter can change states, not just water. They may change states at very different temperatures, however.

**Misconception Alert: Evaporation only happens when something boils.**

**FALSE.** Adding more heat to a substance will *increase* the rate of evaporation, but boiling is not necessary. For example, when you hang a towel up to dry in the sun, water changes from the liquid state to the gas state even though the temperature is well below boiling. Water will also evaporate from soil, lakes, or living things without having to boil.

Water can even go from ice (a solid) to water vapor (a gas). This is called sublimation. You may have seen the result of this as "freezer burn" on food that was frozen too long, especially if the packages were not sealed well.

Molecules of water (or anything else) have the same mass in any state. If you start with 100 grams of water in a closed container, you can freeze it, melt it, evaporate it, or condense it, but it will still weigh 100 grams. The volume will change, however.

**Density** describes how tightly molecules are packed together. The ratio of stuff (mass) to space (volume) is density. Things that are less dense float on things that are more dense. As a substance is heated, the molecules move more, spreading out more. The same number of molecules take up more space. For example, warm air has a lower density than cooler air. That is why hot air balloons rise (Figure 6).

https://www.nasa.gov/aeronautics/nasa-aeronautics-research-on-display-at-albuquerque-balloon-fiesta/

Figure 6. Hot air is less dense than cold air, allowing the hot air balloons to rise. Air heated by the Sun also rises, while colder air falls. We can't see this unless the air is carrying something, such as dust.

Water in its solid state—ice—is less dense than its liquid state. This is unique. Most substances get more dense as they cool, and are most dense as solids. Water follows part of this pattern. Warm water is less dense than cold water, but when ice crystals form, the molecules spread out. Because ice floats on top of liquid water, life can go on below the ice in cold climates in winter (Figure 7). If more of the ice on Earth were in the liquid state, what might happen? Explore this idea in **Why It Matters: Global Climate and Sea Level**.

https://photolib.noaa.gov/Collections/Voyage/Ocean-Exploration/Modern-Expeditions/Arctic-Seas/emodule/1336/eitem/80277

Figure 7. Comb jelly foraging under Arctic ice. Ice is less dense than liquid water. While the ice forms above, the liquid water below still supports many types of life.

**Model Skill: Flow charts**

As discussed earlier, a model is a simplified representation of something. Flow charts use arrows and shapes to show what is happening in a system.

Practice using this skill by turning Figure 8 into a flow chart.

- Turn lines into arrows and label the arrows to describe the transformations.
- Add these labels: melts, evaporates, freezes, and condenses.
- For a challenge, use your own labels to show what is happening with heat to cause the changes, or how density changes as a result.

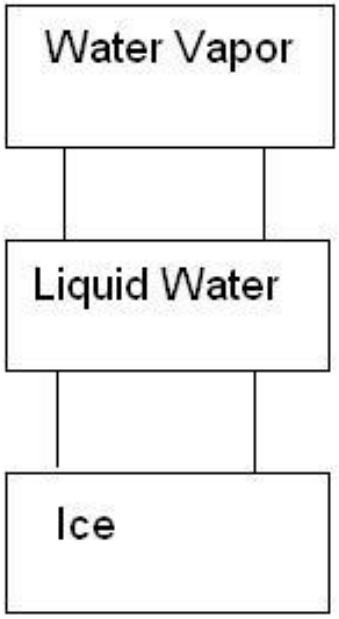
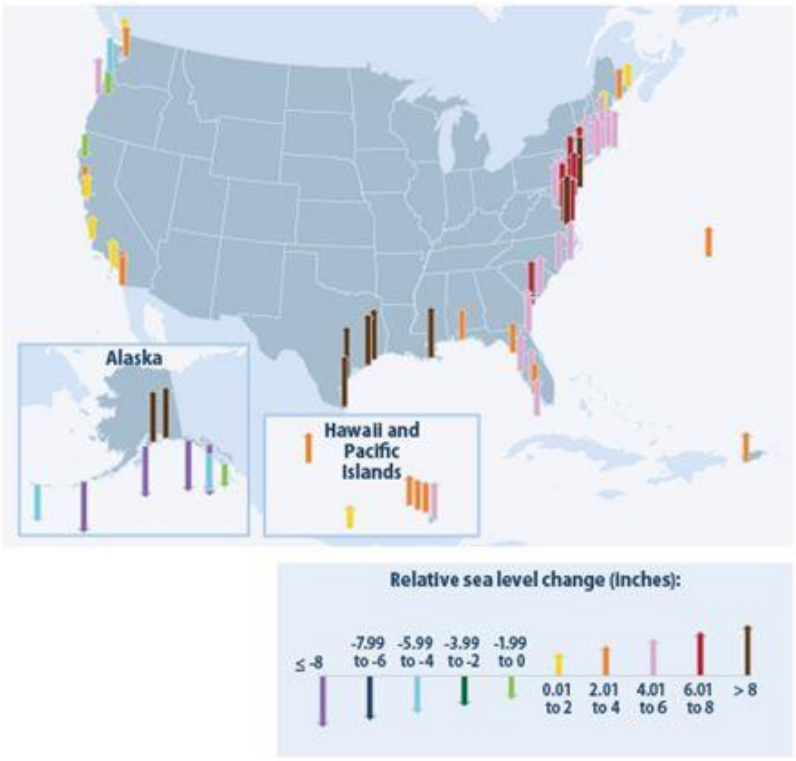



Figure 8. Incomplete flow chart showing states of water.

**Why It Matters: Global Climate and Sea Level**

Many of Earth's largest cities are on coasts. One concern about increasing global temperatures is that sea level will rise. Warm water has a lower density than cooler water, so it takes up more space. Continued melting of ice on land will also add more water to the oceans. For the last 100 years, the global sea level has risen about 1.7 millimeters per year worldwide, but there is a lot of local variation.

Sea level has fallen in some areas and risen in other areas (Figure 9). This is partly because melting glaciers remove weight locally, causing the land to rise. Other areas are sinking. Water level may rise 4-6 feet (122 cm-183 cm) in some areas in the next century.




http://www.epa.gov/climatechange/science/indicators/oceans/sea-level.html

Figure 9. Changes in sea level from 1958 to 2008. Arrows show the direction of change. Colors show the magnitude of change in inches.

- Should rising sea levels be dealt with as a local planning issue or a global one?
- Should we wait for more data before deciding about any action?
- How could flooding in coastal cities cause economic, health, political, and cultural problems?

**Case Study Part 2: Why Won't Trash Go Away?**

https://www.epa.gov/eg/waste-combustors-effluent-guidelines

Figure 10. An incinerator (waste burning plant).

Many communities bury their garbage in landfills. What happens when garbage is buried? Liquids will flow with gravity, seeping down until something stops them. Well-designed modern landfills have liners to prevent liquid waste from seeping into the water and soil below them. However, these barriers can fail. Solids and liquids can be turned into gases by bacteria that release carbon dioxide and flammable methane. Some materials may break down on their own, and become other solids, gases or liquids. Some may be toxic. Every molecule of garbage that is buried in the landfill either stays there or leaks away as a gas or liquid.

Some communities burn their garbage in incinerators (Figure 10). Burning does not make matter disappear; it only transforms it. Some of the solid waste stays solid and becomes ashes. These can be toxic, so they have to be put into sealed containers. These containers must be maintained indefinitely. Some of the solids leave in the smoke, becoming particles in the air. This form of air pollution is a health hazard. Some matter leaves as gases, such as carbon dioxide, water vapor, and carbon monoxide. Some gases may be toxic. Every molecule of garbage that is burned in the incinerator goes somewhere.

**Learning from the Case Study**

- Why won't the trash just go away?
- Does any of the matter become energy? Explain your answer.
- When solids become gases, do they stop being matter? Explain your answer.

**Check Your Understanding**

- Why do water droplets form on the outside of a cold object (such as an ice-filled glass) in a warm room?
- Will a jug of water weigh more when it freezes?
- Why does ice stay on the surface of a frozen lake?
- Why does warm water float on top of cold water?

**Energy cannot be created nor destroyed, but usable energy is lost**

Molecules like water and carbon dioxide are made of matter. They also contain energy in their bonds. **Energy** is the ability to do work. It can take many forms and can be changed from one form to another. Think about all of the work going on around you right now. Every movement you make is work. Your nerve cells fire, allowing you to think. Electric current powers a light bulb. In a nearby plant, **photosynthesis** builds sugar from carbon dioxide and water using energy from the Sun (Figure 11). Energy has no mass and takes up no space.

https://mdc.mo.gov/discover-nature/field-guide/common-sunflower

Figure 11. Sunlight provides the energy that plants need to make sugar molecules from water and carbon dioxide, a process called photosynthesis.

Where did the energy to do this work come from? Your energy comes from eating food, such as an apple. Where did the tree get the energy to make the apple? From sunlight. Where did the electrical current come from? It may have come from burning coal or natural gas. These fuels are the remains of living things that got their energy from the Sun or by eating things that did. Maybe it came from a solar panel, turning light directly into electrical energy. Wind results from the Sun heating air. The wind can turn windmills (Figure 12) that capture this energy. The Sun is the ultimate source of energy for our planet. Like matter, energy can change form, but cannot be created from nothing, nor can it cease to exist. Life on Earth needs a constant supply of light.

https://www.energy.gov/eere/wind/how-do-wind-turbines-work

Figure 12. Windmills capture the kinetic energy to produce electrical current. Wind itself is powered by the Sun heating air masses.

We don't need to add matter to Earth to support life, so why do we need constant input of light? We lose *usable* energy when we transform it. This is the second law of thermodynamics. At first glance, this may seem like it violates the first law of thermodynamics, but keep in mind that when something is "lost" it has not stopped existing. For example, imagine that I save a large bag of pennies. I attach them to my bicycle and ride to the credit union to turn them in. When I get there, I find a hole in the bag. My pennies are now scattered over a very long stretch of road. There are just as many pennies in the universe as there were an hour before, but they are dissipated (spread out) over a large area. Gathering them up again would cost me more than they are worth. When energy is transformed, some is dissipated. The energy doesn't stop existing but gathering it up again would take more energy than would be gained.

Another way to put this is that systems tend to go from order to disorder. As an analogy, you may clean your home on Monday, but it will probably be less orderly as the days go by. How can you make a system orderly again? With work, which is powered by energy. The tendency to go from order to disorder on the molecular level is called **entropy**. Entropy can also be reversed by adding energy. The input of energy from the Sun powers the work needed to create the order of life from disorder. This idea is explored more in **Evolutionary Perspective: Addition of Energy Makes Evolution Possible**.

**Evolutionary Perspective: Addition of Energy Makes Evolution Possible**

The first organisms on Earth were very simple. As life evolved from the first species, organisms became larger and more complex. Some people mistakenly believe that this is not possible because of entropy—the tendency of systems tend to go from order to disorder.

Evolution does not violate the laws of thermodynamics. The input of energy allows for greater organization. This is the same reason that you were able to develop from one fertilized egg into trillions of specialized cells. Energy from your mother, and then from food you ate allowed the making of complex molecules and the organization of your body. In the case of evolution, energy from the sun provides energy—directly or indirectly—that allows order to increase. (There are other energy sources on Earth, but the sun is vastly more important.)

What is this dissipated energy? It is energy in the form of heat. Heat is the movement of molecules. When we transform one type of energy into another type efficiently, there is very little heat loss. Old fashioned incandescent light bulbs emitted a lot of heat. Modern household lighting gives off a lot less heat, though no energy transformation is completely efficient.

https://www.energy.gov/eere/new-energy-efficiency-standards-lightbulbs-what-you-need-know

Figure 13. Modern lightbulbs are more efficient in transforming electrical energy into light energy.

**Check Your Understanding**

- Give your own example of changing one form of energy to another.
- How could you compare the efficiency of two different engines of the same size? [Hint: what is a simple measurement you could take?]
- Why does Earth need a constant supply of energy to support life?

**Energy Can Be Potential or Kinetic**

We divide the many types of energy into two major categories: **potential energy** and **kinetic energy** (Table 1). Kinetic energy involves movement. Electrical current, sound, light, heat, and movement of an object are all forms of kinetic energy. Potential energy is stored energy. The name is rather misleading. You are a potential college graduate if you are not yet a college graduate. Potential energy is already energy. It has the potential to do work.

Energy can be stored in many forms. For example, doughnuts and gasoline contain energy in the chemical bonds in their molecules. That energy can be released to make a person or a car move. A coiled spring contains potential energy. An apple at the top of a tree contains potential energy due to its position.

Table 1. Examples of types of energy.

| Potential Energy | Kinetic Energy |
|---|---|
| Charged Battery | Moving Toy |
| Rock on a Hill | Rolling Rock |
| Water in a Reservoir | Flowing Water |
| Fat | Person Moving |
| Gasoline | Engine Parts Moving |

The different types of energy can be converted into each other. Imagine a cyclist riding her bike on a hill (Figure 14). A cyclist uses up some of her potential energy (stored as sugars, glycogen, or fat) to do work (muscle movement is kinetic energy) to get to the top of the hill. On top of the hill, the bike and rider have more potential energy than they do at the bottom. The cyclist can coast down the hill, transforming some of the potential energy into kinetic energy. The cyclist will not be able to coast up another hill of equal height without pedaling because some of the energy has been dissipated as sound and heat (the greater the friction of tires on the road, the lower the efficiency).

Figure 14. Transforming energy as a cyclist rides up and down a hill.

**Analyze the Figure**

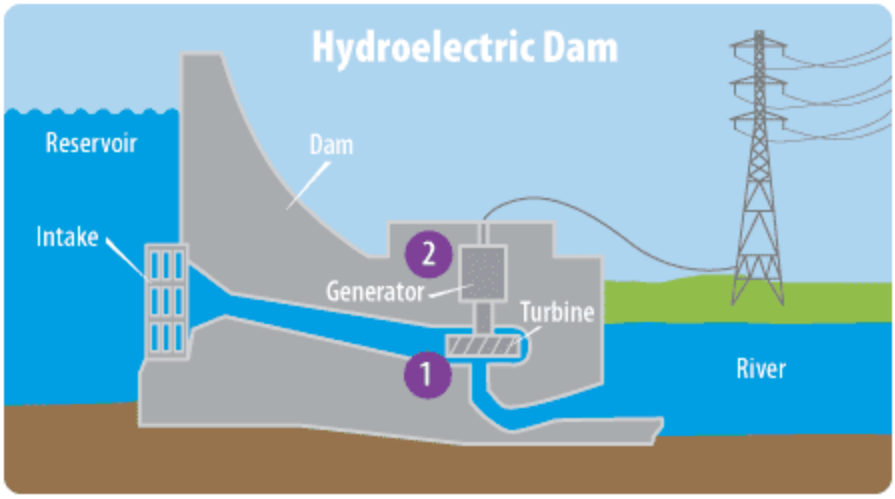
- Where does the cyclist have the most potential energy due to position?
- What is the source of energy that the cyclist used to do the work of climbing the hill?
- Why would the cyclist produce body heat going up the hill?

You can demonstrate this same concept yourself using the experiment in **Do Try this at Home: As Energy is Transformed, Some is Lost**.

**Do Try this at Home: As Energy is Transformed, Some is Lost.**

What you will need: a bowl (the rounder, the better) and a marble. Hold the marble at the top of the inside edge of the bowl, then release it. If all the potential energy were converted into kinetic energy in the form of marble movement, the marble would reach the top of the bowl on the other side. Does it? What is happening to the energy? Where does some of the kinetic energy go?

It is not always obvious how the Sun provides the energy we use each day. The potential energy of water behind a dam can be converted to kinetic energy as water flows through gates (Figure 15). The water can turn machines called turbines. The movement of the turbines is also kinetic energy. The turbines transform that movement into electrical current. When you plug in a battery charger, you take the kinetic energy of the current and transform it into the potential energy of a charged battery. The batteries can power a flashlight. When you turn on the flashlight, you transform this potential energy into kinetic energy in the form of light.




https://archive.epa.gov/climatechange/kids/solutions/technologies/water.html

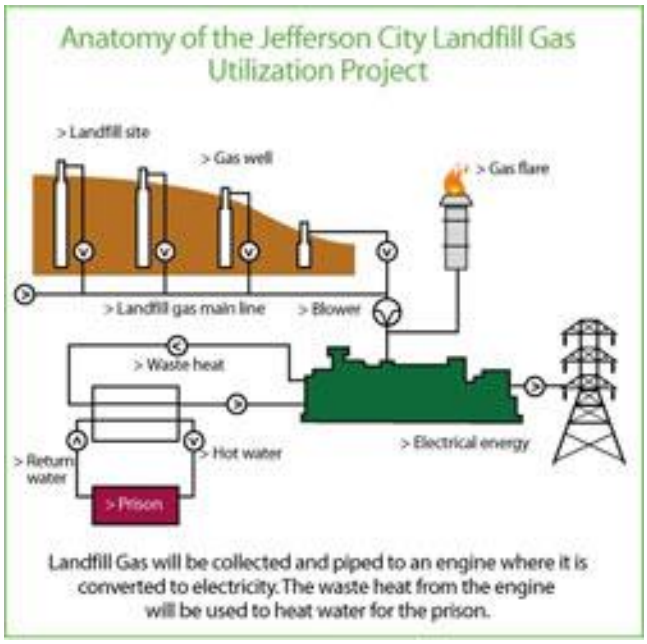
Figure 15. Electrical energy production from a hydroelectric dam. Movement of water through turbines is transformed into electrical current. The electrical energy is not being produced from nothing, it is being transformed from another type of energy. This is an example of potential energy being transformed into kinetic energy.

**Analyze the Figure**

- Identify the potential energy in the figure.
- Identify at least two types of kinetic energy in the picture.
- How did the water get into the reservoir?

What was the source of the energy to begin with? The Sun provided the energy to evaporate the water that later condensed and fell upstream from the dam. Only a small fraction of that energy is available to turn on the flashlight because some was lost each time the energy was transformed.

**Case Study Part 3: Can We Recapture the Energy in Garbage?**




https://www.epa.gov/lmop/landfill-gas-energy-project-data

Figure 16. A system for capturing landfill methane in Jefferson City, MO, USA.

The complex molecules in garbage contain potential energy in their bonds. Can we use the energy in garbage? We can capture *some* of it. Some modern landfills were designed to capture the methane given off when bacteria break down the garbage. Methane is separated from other gases and used to produce electrical energy. Collecting and purifying the methane requires energy, but there is a net gain in energy that would otherwise be wasted. When methane burns, most of it is broken down into carbon dioxide, carbon monoxide, and water vapor.

Some modern incinerators recapture part of the heat that is produced when garbage is burned. It takes a lot of heat to burn the garbage, however. Think about what is in most dumpsters. Some garbage is very wet. Some of it will not burn at all. Some will burn only if a lot of heat is used. Heat is also lost in the process of producing usable energy.

**Learning from the Case Study**

- Is it possible to recapture all the energy released when garbage burns? Explain your answer.
- Does any of the matter in garbage become energy? Explain your answer.

**Check Your Understanding**

- What is the key difference between potential energy and kinetic energy?
- What is the source for almost all energy on Earth?
- Can all the potential energy stored in anything be used to do work? Explain your answer.

**Organisms are Made of Molecules**

A few general types of molecules are found in all living things. We have already discussed the importance of water. Carbohydrates are a group of molecules that are also common in all organisms. Carbohydrates are made of carbon, hydrogen, and oxygen atoms. Sugars are the simplest carbohydrates (Figure 17). Some chains of sugars become the starches plants use for storing energy.

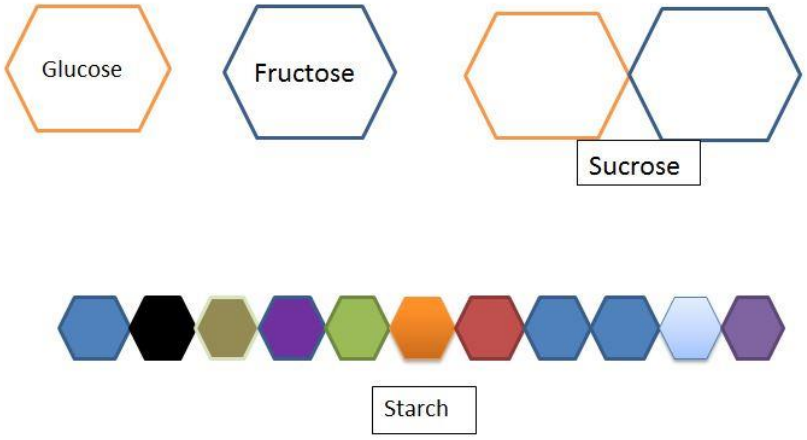



Figure 17. Simplified diagram showing how simple sugars—such as glucose and fructose—can be joined together into more complex sugars or into long chains of starches.

Other chains of carbohydrates become cellulose or wood, giving plants their structure (Figure 18). Animals also contain sugars, but are not made of starch, cellulose or wood. Animals can store energy as glycogen. For more on glycogen, see **Make the Medical Connection: Glycogen, Endurance, and Fad Diets.**

Burton, 2014

Figure 18. Plants are made of a variety of carbohydrates, along with other biological molecules.

**Make the Medical Connection: Glycogen, Endurance, and Fad Diets**

Animals, including humans, store most of their excess energy as fat, but they also store some as glycogen. Our glycogen is a short-term source of energy stored in our liver and muscles. Endurance athletes may load up with carbohydrates the day before they compete to increase their glycogen levels. This glycogen, and some fat, provides energy during exercise.

There is a limit to how much glycogen we can store because it is stored with 2-3 times its weight in water. When people starve themselves of carbohydrates, they burn most of their glycogen and also lose that water. They can have dramatic short term weight loss that has nothing to do with fat loss. This weight will be regained as they rehydrate and return to normal eating. The weak, tired, and irritable feelings that happen with a lack of carbohydrates may discourage exercise, so a fad diet may cause more fat gain in the long term.

Fats are also made from carbon, hydrogen, and oxygen. These molecules store energy and have other critical roles in living things, such as providing padding and insulation, and giving

shape to the body (Figure 19). Fats come in different forms. For more on this, see **Make the Medical Connection: Saturated and Unsaturated Fats.**

Burton, 2014

Figure 19. These sea lions (*Zalophus wollebaeki*) store energy as fat. Fat also provides insulation from the cold water and gives their bodies a shape that moves easily through water.

**Make the Medical Connection: Saturated and Unsaturated Fats**

https://calfreshhealthyliving.cdph.ca.gov/en/tips/Pages/Oil-and-Fats.aspx

Figure 20. Examples of foods containing plant and animal fats.

You have probably heard that saturated fats may lead to health problems. A saturated fat is "saturated" with hydrogen. It has no double bonds, so it is solid at room temperature. Butter, lard, and the solid fat in meat are saturated fats.

An unsaturated fat has double bonds. This causes kinks in the molecule and keeps it liquid at room temperature. Olive oil, corn oil, and safflower oil are all examples of unsaturated fats.

Trans fats—such as margarine— are made when hydrogen is added to unsaturated fats such as vegetable oil to make them solid at room temperature. Trans fats may increase the risk of heart disease.

Proteins have many roles in structure, movement, and regulation (Table 2). Along with carbon, hydrogen, and oxygen, they contain nitrogen.

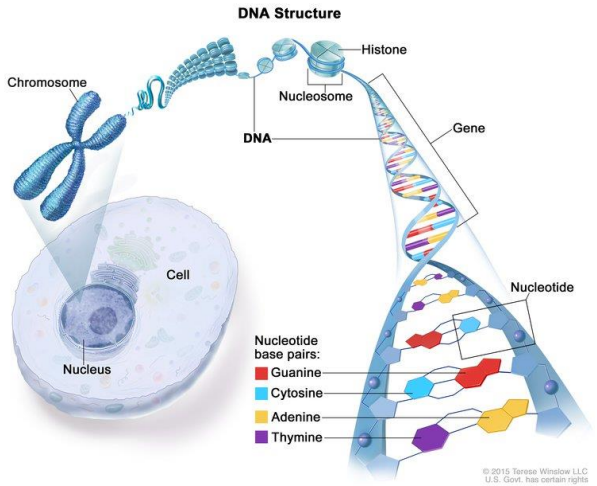
Table 2. Some of the many types of proteins found in organisms.

| Type | Function |
|---|---|
| Hormones | Regulate Functions |
| Connective tissues | Give form, movement, and strength |
| Antibodies | Fight disease |
| Enzymes | Speed up reactions |
| Transporters | Allow movement of molecules |

Burton, 2009

Figure 21. Proteins are part of the muscles, fur, horns, and hooves of the wildebeest (*Connochaetes taurinus*). They are also critical to its physiology and behavior.

DNA—which holds the recipes for life—contains all of these elements (C, H, and O) and phosphorus. All living things contain DNA. If the cell has a nucleus, the DNA is found there (Figure 22). DNA takes information from one generation to the next in reproduction (Figure 23). The role of DNA will be explored more in Chapter 4.




https://visualsonline.cancer.gov/details.cfm?imageid=10062

Figure 22. DNA in a cell. DNA is wrapped around proteins to make chromosomes, which are found in the cell. Some organisms have a nucleus inside the cell, which contains the DNA. Bacteria have DNA, but no nucleus.

Burton 2009

Figure 23. DNA is the molecule that passes information from one generation to the next. The baby gorilla (*Gorilla gorilla*) got half its DNA from its mother.

**Check Your Understanding**

- What are some forms of fat?
- What atom is found in protein, but not in fats or carbohydrates?
- What is the role of DNA in living things?

**Matter and Energy Move Through Ecosystems**

Ecologists study how matter and energy flow between living things and their environment. Energy arrives on Earth as sunlight (Figure 24). Producers—such as plants and algae—use energy from the Sun to do photosynthesis. They use this energy to make complex molecules like carbohydrates, proteins, and fats. Consumers—such as animals and fungi—take in these large molecules and break them down to get energy and raw materials for new molecules. Decomposers break down dead material and wastes. Decomposition makes the raw materials and some of the energy available to other organisms.

https://wwwipat.fisheries.noaa.gov/national/habitat-conservation/shallow-coral-reef-habitat

Figure 24. Coral reefs only exist in shallow water where sunlight is available. The algae that live in corals need energy from light to make carbohydrates that the corals use. The corals—which are animals—provide nitrogen to the algae.

Because they are matter, nutrients are recycled in ecosystems (Figure 25). Organisms take in matter (water, nutrients, and gasses) and give it back to the environment in a cycle. All living things need raw materials (atoms) to make their molecules. The most common atoms in these molecules are carbon, hydrogen, oxygen, nitrogen, and phosphorus. Many other elements may only be needed in small amounts or by certain types of living things. Any of these elements may be called nutrients.

Energy also flows through ecosystems, but its pattern is different. While matter is recycled, energy is lost every time it is transformed. Energy must constantly enter the ecosystem because the heat energy will dissipate (spread out) and will no longer be useful to do the work of the living organisms in the ecosystem. Chapter 5 will discuss the details of these cycles.

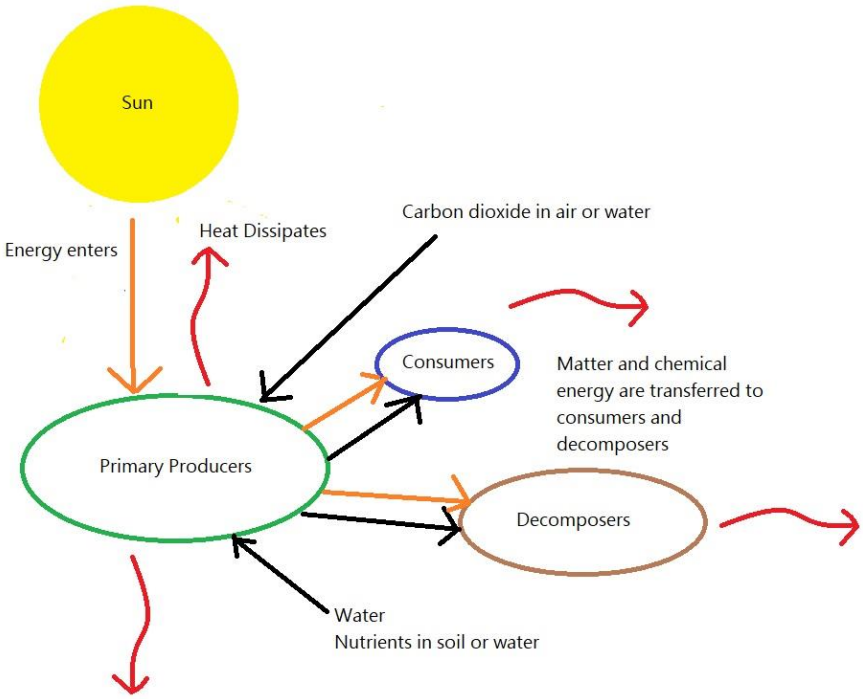



Figure 25. A model of matter and energy movement in an ecosystem. Producers use solar energy and matter to produce molecules that consumers and decomposers use as matter and energy sources. All organisms lose energy as heat.

**Analyze the Figure**

- Where does the energy in producers go?
- What eventually happens to all energy?
- How does matter get from consumers back to producers?

As the Sun's rays strike earth, some of the energy is reflected. Some is absorbed by matter on Earth and released as heat. Gases in the atmosphere trap some of that heat. **Greenhouse gases** such as carbon dioxide, methane, carbon monoxide, and water vapor increase the thickness of this layer, trapping more heat (Figure 26). This can result in increasing global climate change. For more on efforts to reduce greenhouse gases, see **Hypothesis Testing: How Green are Biofuels?**

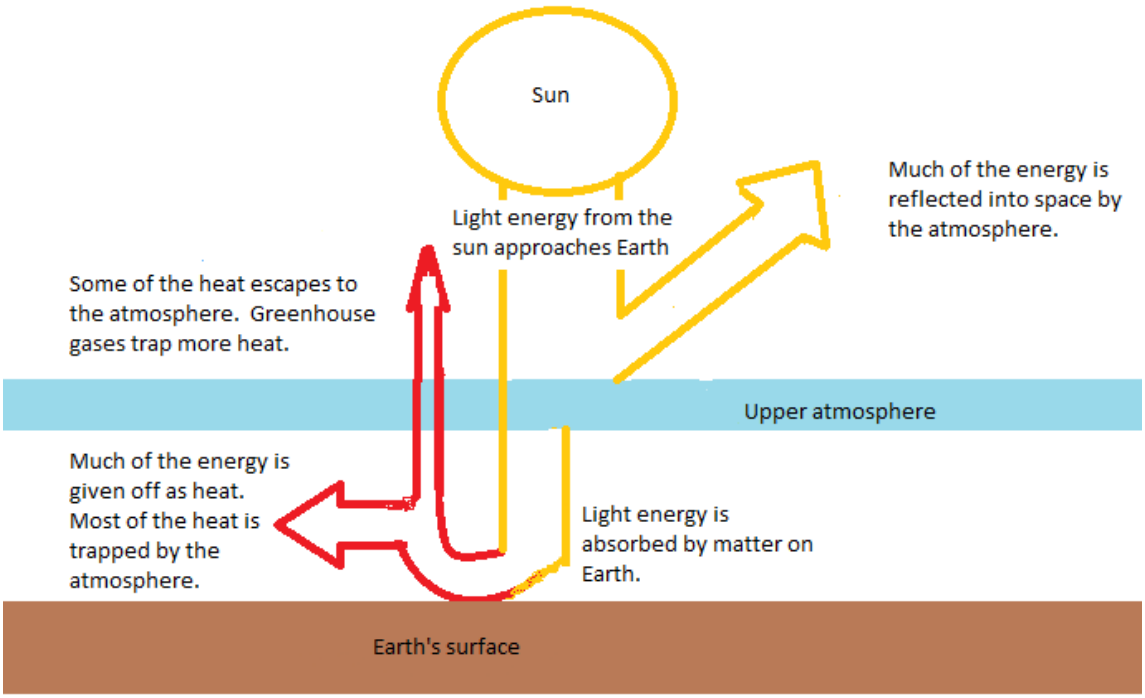
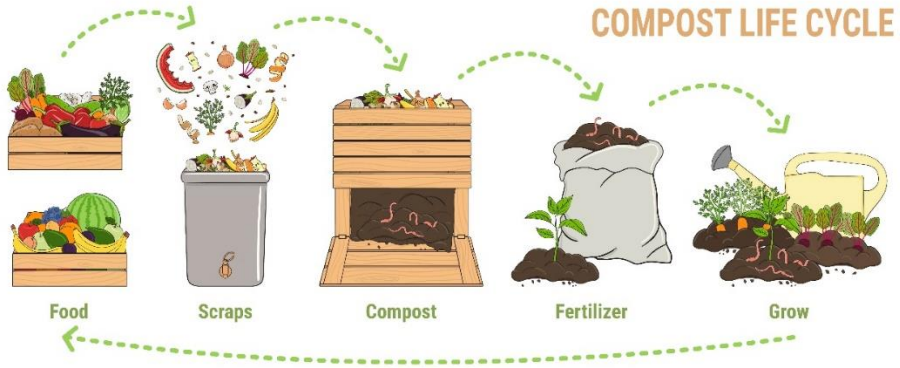



Figure 26. Energy entering from sunlight has several possible fates when it reaches Earth. Greenhouse gases trap heat in Earth's atmosphere.

**Analyze the Figure**

- Name some possible things that can happen to sunlight that reaches Earth.
- Why would a thicker atmosphere lead to increased temperatures on Earth?

**Case Study Part 4: Can We Create Less Garbage?**




https://www.alexandriava.gov/waste/backyard-composting-0

Figure 27. The composting cycle. Plant waste is broken down by decomposers. The resulting compost is used to grow more plants.

The saying “reduce, reuse, recycle” encourages people to buy less, repair or re-use (or give away) items, and recycle whenever possible. Recycling means that a used item is broken down, then used to make new materials. Some materials—such as aluminum—can be recycled over and over. Others—like paper—lose some of their quality with recycling. Shorter recycled paper fibers are mixed with new paper fibers to create some forms of paper. Recycling requires energy, but usually less energy than making new materials.

Composting is a form of natural recycling (Figure 27). The biological molecules in waste can be broken down by living organisms. Much food waste and yard waste can be composted instead of being sent to landfills or incinerators. Bacteria, insects, worms, and other decomposers break down the large molecules into carbon dioxide, water, and other molecules. If other living things eat the decomposers, energy is returned to the ecosystem. The material left over from composting—compost—contains nutrients. It can be mixed into soil and used for growing more plants. Some materials that could be broken down by decomposers (such as meat) are not added to home compost containers because they attract pests and create unpleasant smells.

**Learning from the Case Study**

- Is it possible to recapture all the energy in food waste when it is composted? Explain your answer.
- Does any of the matter in compost become energy? Explain your answer.

**Hypothesis Testing: How Green are Biofuels?**

Producing usable energy from plants seems like a way to reduce environmental damage caused by the extraction, processing, and use of fossil fuels such as gas and oil. However, the question becomes more complex when we examine all the matter and energy streams involved in producing various biofuels. The question is also complicated because there are many types of biofuels and fossil fuels.

Hypothesis: Biofuels have a lower environmental impact than fossil fuels.

Zah et al. (2007) made a comprehensive study of several types of biofuels and fossil fuels and looked at many dimensions of their environmental costs in Switzerland. They performed a lifecycle analysis (LCA) that tracked all the matter and energy needed to produce the fuels. The researchers did not try to measure the economic or social costs (such as quality of life for agriculture workers vs. petroleum industry workers).

A major environmental cost is the production of greenhouse gases such as carbon dioxide ($CO_2$). $CO_2$ emissions of biofuels were analyzed over the lifecycle of production: Infrastructure (such as costs of roads and bridges), cultivation (such as tilling and harvesting), production (such as refining or distilling), fuel transport, and vehicle operation. Processes vary and transportation is dependent on where raw materials and

products are shipped, but different biofuels have very different impacts (Figure 28). Gasoline is grouped with ethanol because ethanol is often added to gasoline.

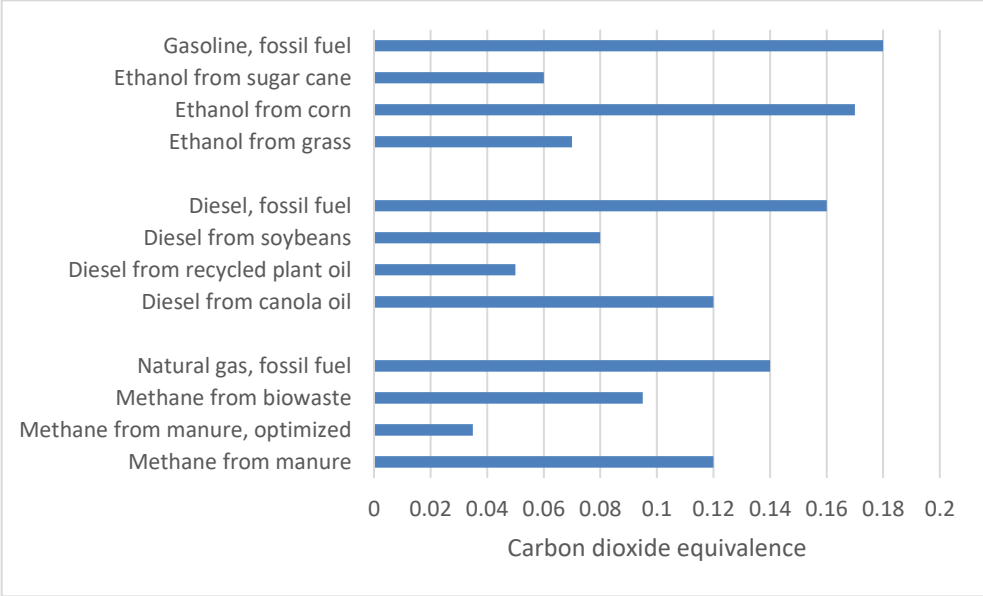



Figure 28. Amount of carbon dioxide produced during the life cycle of various fuels. Modified from: Zah, R., Böni, H., Gauch, M., Hischier, R., Lehmann, M., & Wäger, P. (2007). Life cycle assessment of energy products: environmental assessment of biofuels. *Empa Technology and Society Lab. Bern, Switzerland*, 19.

**Analyze the Figure**

- Which fuels produced the lowest total $CO_2$ emissions?
- Did the type of crop make a difference in $CO_2$ emissions? Provide an example.
- How does this information support or refute the hypothesis?

Agriculture consumes energy for transport of materials, manufacture of fertilizers and pesticides, cultivation, processing of crops, and other processes. Irrigation may deplete water resources. Fertilizers, pesticides, and soils pollute water. Expanding farmland usually means decreasing wildlife habitat. Extracting and refining fossil fuels requires energy and produces air and water pollution. Burning fuels produces air pollution and acid precipitation. The European Eco-indicator 99 combines several indicators of environmental damage into one number to allow comparison of practices. Zah et al. (2007) used one graph to simultaneously show the greenhouse gas emissions and overall environmental impact of different biofuels (see a modified version in Figure 29).

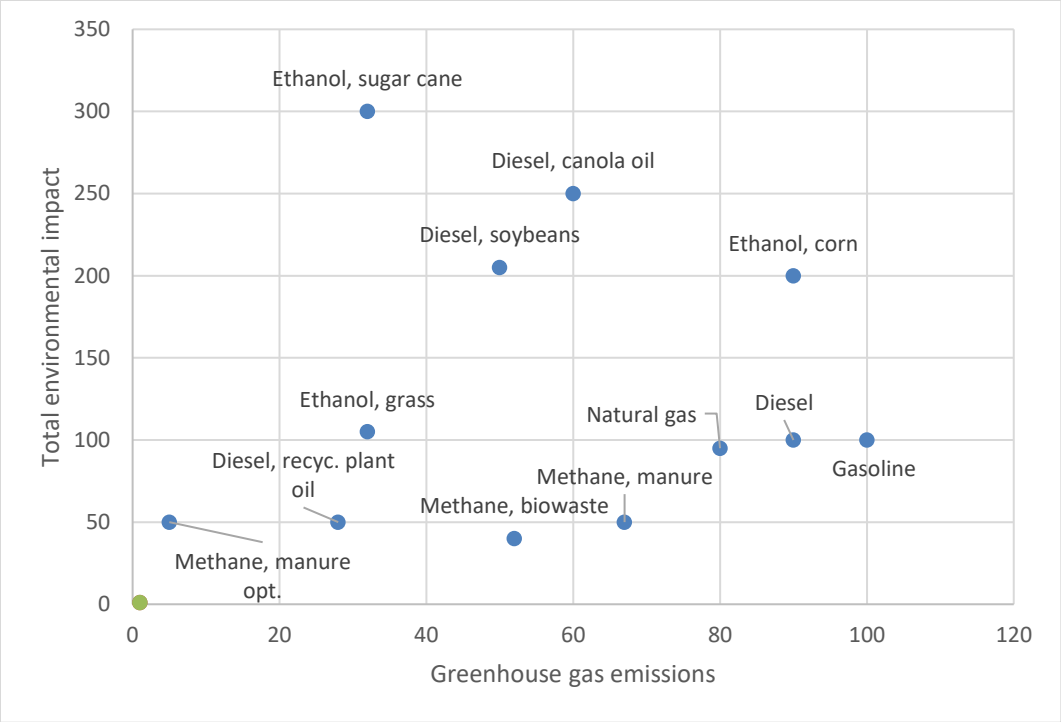



Figure 29. Total environmental impact (as a percent of the impact of gasoline) and carbon dioxide produced during the life cycle of various fuels. "Opt." means optimal. Modified from: Zah, R., Böni, H., Gauch, M., Hischier, R., Lehmann, M., & Wäger, P. (2007). Life cycle assessment of energy products: environmental assessment of biofuels. *Empa Technology and Society Lab. Bern, Switzerland*, 19.

**Analyze the Figure**

- Which fuels had a low environmental impact and low greenhouse gas emissions?
- Which fuels had high environmental impact and greenhouse gas emissions?
- How does this information support or refute the hypothesis?

Zah et al. also pointed out that specific regulations, such as requiring systems that do not leak gases, or banning the clear-cutting of tropical forests could make production of biofuels more environmentally friendly.

Looking at only one aspect of any product or practice may provide a misleading picture of environmental impact. Tracing the lifecycle of all energy and matter in the system gives a more complete understanding of environmental impact.

**Evaluate the Hypothesis**

- Do biofuels have a lower environmental impact than fossil fuels?

**Check Your Understanding**

- How are the pathways of energy and matter in ecosystems different?
- Why are decomposers a critical part of ecosystems?
- Which group is more critical to ecosystems, producers or consumers? Explain your answer.

# Key Concepts

- Matter can neither be created nor destroyed. Its state (solid, liquid or gas) and density can change depending on heat. This is the first law of thermodynamics.
- Energy is the ability to work. It can be potential (stored) or kinetic (involving movement).
- Energy can neither be created nor destroyed. When it changes, some of the usable energy is dissipated as heat. This is the second law of thermodynamics.
- The key molecules in living things include water, carbohydrates, fats, proteins, and DNA.
- Matter cycles in ecosystems. Energy travels through ecosystems, but is dissipated, so life on Earth depends on continued energy input from the sun.

# Apply the Concepts

**Learning Outcomes**

1. *Clearly explain how matter is conserved and transformed.*
2. *Make valid predictions about how changes in heat will lead to changes in states and density of matter.*
3. *Clearly explain how energy is conserved, transformed, and dissipated.*
4. *Accurately identify functions of key molecules found in living organisms.*
5. *Clearly describe how energy and matter move through ecosystems.*

1. Suppose that you had a large container of water.
   A. If the water froze, would its weight (mass) change? Explain your prediction. *(Learning Outcomes 1 & 2)*
   B. Would it have more potential energy on the floor or on a high shelf? Explain your reasoning. *(Learning Outcome 3)*
   C. If there were a hole in the bottle, would the water flowing out of the hole be an example of potential energy or kinetic energy? Explain your reasoning. *(Learning Outcome 3)*

2. Suppose that exercising for 20 minutes burns 100 calories. If you eat a granola bar that contains 100 calories, will that replace all of the calories you burned while exercising? Explain your prediction. *(Learning Outcome 3)*

3. Imagine that you are making microwave popcorn in a sealed bag. The entire bag, including the popcorn, oil, and salt, weighs 4 ounces (about 113 grams).
   A. After popping, how much will the entire sealed bag and contents weigh? Explain your prediction. *(Learning Outcome 1)*

B. Will the volume of the bag and contents have changed? Explain your prediction. (*Learning Outcomes 1 & 2*)
C. Will the density of the entire bag and contents have changed? Explain your reasoning. (*Learning Outcomes 1 & 2*)

4. Why do many plants grow better when they are treated with fertilizers that contain nitrogen and phosphorus? What important biological molecules contain these elements? (*Learning Outcomes 4 & 5*)

5. Speculate about why scientists are so interested in whether other planets or moons have water in liquid form. *(Learning Outcome 4)*

6. Imagine that a classroom has a covered tank containing water, algae (a producer) and some small animals that eat algae. Explain why the students do not have to add nutrients, but they do have to provide light. *(Learning Outcome 5)*

7. Suppose that you want to buy a laptop computer that uses the least amount of power. You see three computers that have about the same features. You borrow an infrared thermometer from a nearby display and get the following information:

| | |
|---|---|
| Computer A | 27 $^{o}$C |
| Computer B | 32 $^{o}$C |
| Computer C | 30 $^{o}$C |

A. Which computer is the most energy-efficient? Use the data and key concepts to explain your reasoning. *(Learning Outcome 3)*
B. Evaluate this conclusion. Are there other factors that could have influenced the temperature you measured? *(Learning Outcome 3)*

**Unit I: Knowing the World through Ecology**

# Chapter 4: How Life Works

### Case Study Part 1: It's Alive!

http://oceanexplorer.noaa.gov/explorations/05lostcity/logs/july27/media/xeno2.html

Figure 1. Xenophyophore, a giant cell that lives deep in the ocean.

It sounds like a monster movie. Xenophyophores (pronounced "zee-no-FY-o-fores") are giant cells (up to 20 cm across) that live on the ocean floor. They surround food and pull it into their bodies. They spread large pools of their own mucus. Their name means "bearer of foreign bodies" and it refers to their habit of building protective shells—tests—from junk and their own feces.

### Learning from the Case Study

- What characteristics of this creature tell you that it is alive?
- What other characteristics would a living being have?

# Learning Outcomes

- *Accurately identify characteristics of living things*
- *Explain basic nature of cells*
- *Correlate DNA function with the continuity and diversity of life.*
- *Correctly apply the concepts of evolution by natural selection*
- *Correctly apply concepts of classification of living things*

**Vocabulary Toolkit**

**Roots**

Uni = one
Multi = many
Eu = good
Pro = early/first
Micro = small
Macro = big

**Word Watch List**

**Metabolism**: Chemical reactions in organisms
**Homeostasis**: Process of maintaining an organism's state within limits
**Eukaryotic**: Describes cells with membrane-covered organelles and nucleus
**Prokaryotic**: Describes cells without membrane-covered organelles and nucleus
**Membrane**: Semi-fluid covering of the cell and some organelles
**Unicellular**: Made of one cell
**Multicellular**: Made of multiple cells
**Gene**: Segment of DNA coding for a protein
**Genotype**: Individual's set of genes
**Phenotype**: Individual's characteristics resulting from genotype and environment
**Chromosome**: DNA wrapped around proteins
**Mother cell**: Cell that divides to make daughter cells
**Daughter cell**: One of two cells made when a mother cell divides
**Mutation**: Change in DNA
**Allele**: Variety of a gene
**Sexual reproduction**: Procreation that involves exchange of DNA
**Gametes**: Sex cells (eggs and sperm) used in sexual reproduction
**Asexual reproduction**: Procreation that does not involve exchange of DNA. Offspring are identical to each other and parent
**Dominant**: A trait that appears whether there are 1 or 2 copies of the allele
**Recessive**: A trait that appears only when there are 2 copies of the allele
**Fitness**: Leaving relatively more offspring than other members of the species
**Natural selection**: Change in gene proportions caused by genetic variation and difference in fitness in a specific environment
**Evolution**: Change in proportions of genes in a population
**Microevolution**: Genetic change within a species
**Macroevolution**: Genetic change that results in new species
**Hybrid**: Offspring with parents of two different species

## Living Things Share Characteristics

All organisms use matter, energy, and information to leave offspring that are similar to themselves (Figure 2). As discussed in Chapter 3, any system tends to go from order to

disorder. Living things use energy from light or complex molecules (food) to go from disorder to order. They create, grow, and maintain highly organized systems, including structures and chemical reactions. All the chemical reactions in an organism make up its **metabolism**. This includes breaking things down (digestion, destroying damaged or unneeded structures, and killing invaders) and building things up (healing, growth, reproduction, and production of substances).

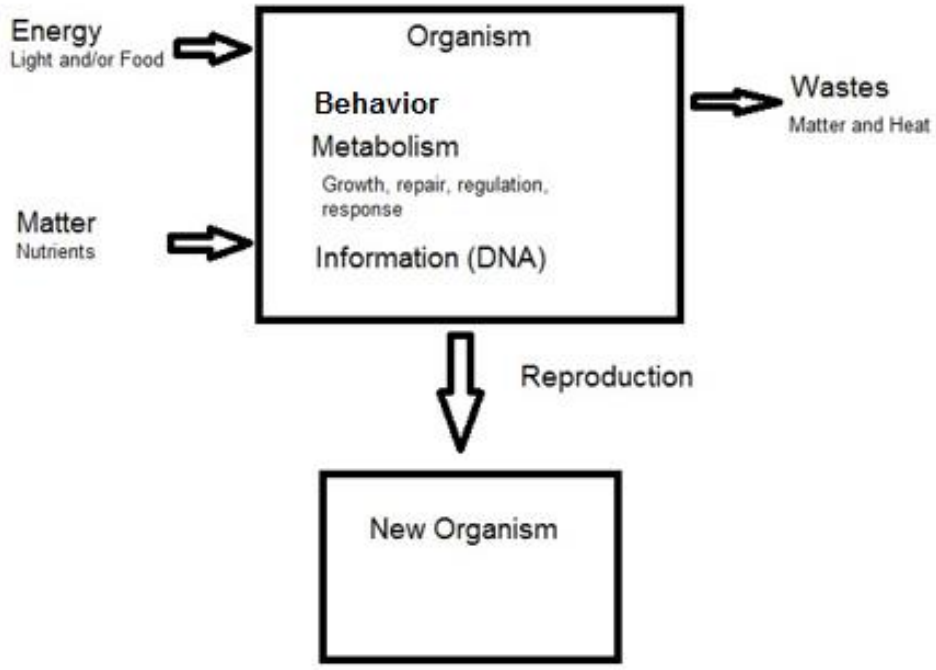



Figure 2. Model of an organism, showing inputs (energy and matter), outputs (wastes), and processes (behavior, metabolism and information transfer).

Metabolism also produces wastes. All living things produce wastes, but the wastes of one organism may be resources for other organisms. The wastes can be liquid, solid, or gaseous. Heat energy is produced by many chemical reactions. It can be essential to an organism, but excess heat can be a waste product.

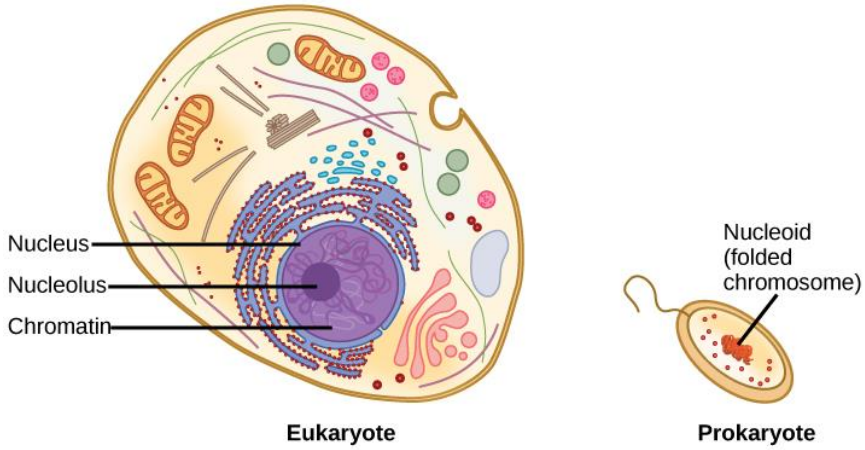
Living things respond to their environments in ways that tend to increase their ability to survive and reproduce. The type of cues in the environment and the reactions may be very different. For example, animals might move to avoid a predator. Plants might respond to an insect attack by making toxic chemicals. Bacteria my create a tough outer covering when their environment gets cold and dry.

Organisms also maintain fairly stable internal environments—a process called **homeostasis**. For example, your body is constantly attempting to regulate your blood sugar, blood pressure, body temperature, and many other levels within certain ranges. Other organisms may be

regulating different things in different ways, but the concept is the same. This regulation also requires energy and matter. When they cannot maintain their internal environments within specific limits, organisms die.

Cell theory states that all living things are made of one or more cells, and all cells come from other cells. Recall from Chapter 1 that a theory is not just a guess. It explains many different things, has a large amount of supporting evidence, makes valid predictions, and helps to organize knowledge. It is possible that life exists elsewhere in the universe without cells, but no evidence of this has yet been found. Cells are the smallest unit of life as we know it. Viruses have DNA, but they have no cells, so they are not considered living organisms.

All cells have a cell **membrane** (also called a plasma membrane) that regulates what enters and leaves the cell (Figure 3). Inside the membrane is fluid containing various molecules and structures. The fluid allows things to move around so that they can interact, be expelled, or travel to where they are needed. The metabolic processes of life happen within the cell or between cells. As discussed in Chapter 3, all cells have DNA, which provides Information that guides an organism's structure and activity. It is also passed from one generation to the next, no matter how an organism reproduces.




https://oertx.highered.texas.gov/courseware/lesson/1676/student/?section=7

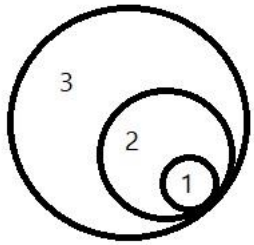
Figure 3. Generalized cells. Eukaryotic cells are usually about 10 times bigger than prokaryotic cells. Using one picture to represent all cells is similar to drawing one picture to represent all animals. Cells have general features in common but will also vary depending on their evolutionary history and their function.

**Eukaryotic** cells have a nucleus, which is a membrane bag containing the DNA. Some of their organelles are covered with membranes. **Prokaryotic** cells are much smaller than eukaryotic cells. While all cells have DNA, the DNA of prokaryotes is not in a nucleus. Prokaryotes also lack membrane-covered organelles, which are found in all Eukaryotes. Prokaryotes are almost always **unicellular** (made of one cell). Eukaryotes may be unicellular or **multicellular** (made of

many cells). It is tempting to call prokaryotic cells simple, but they contain all the structures and metabolic pathways they need to carry out life.

**Case Study Part 2: A Giant Cell**

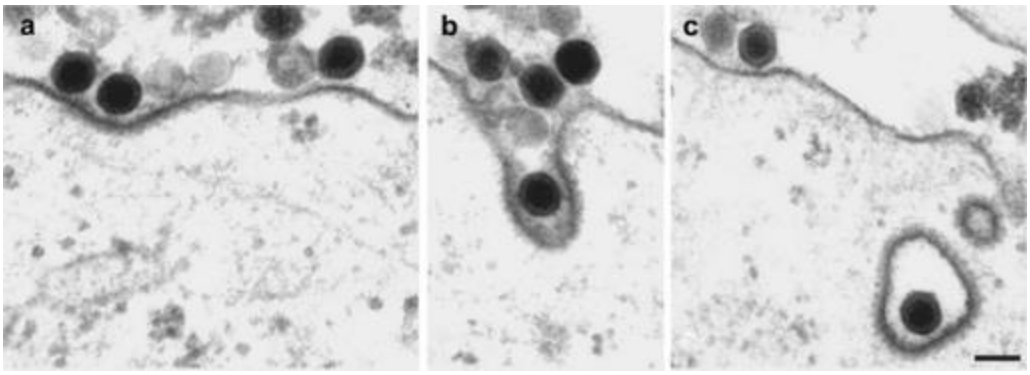
Cells are usually so small that you need a microscope to see them. This gives them a lot of surface area for every unit of volume (Figure 4). Picture wrapping a shoebox in paper. If you wrapped two shoeboxes together, you would need less paper than wrapping two separately. The "wrapping" around each cell is its membrane. Smaller cells have proportionately more membrane than large cells. The membrane controls what goes into or out of a cell, so having more membrane is usually useful to the cell. In a large cell, the center of the cell can be a long way from the outside—the source of gases, energy, and nutrients. This means a slow delivery of these important resources.




| Radius | Surface | Volume | Surface: volume |
|---|---|---|---|
| 1 | 1 | 1 | 1:1 |
| 2 | 4 | 8 | 1:2 |
| 3 | 9 | 27 | 1:3 |

Figure 4. As the radius of a sphere triples, the surface area gets 9 times bigger, and its volume gets 27 times bigger. The ratio of surface to volume goes from 1:1 to 1:3. In other words, as cells get bigger, they have less area for exchanging inputs and outputs with their environment.

Why are the xenophyophores such large cells? One reason might be that it gives the organism more options in the size of food particles. Xenophyophores feed the same way amoebas do, by grabbing the food with extensions of their membranes and bringing it into the cell (Figure 5). A small cell could only grab very small particles. Food can be very scarce in the deep ocean, so being able to eat food of many sizes could be a major advantage.




http://openi.nlm.nih.gov/detailedresult.php?img=3038234_709_2010_152_Fig3_HTML&req=4

Figure 5. This series of photographs was taken with a powerful electron microscope. It shows virus cells being "eaten" by a cell. Only a small portion of a cell is visible. In **a**, pits form on the cell membrane. In **b**, the pit becomes deeper, and the edges of the membrane start to close behind the virus. In **c**, the virus has been engulfed by the cell. This process is similar to how xenophyophores eat.

These giant cells are also odd because they have several nuclei. Most cells with a nucleus have only one. Recall that DNA is stored in the nucleus and provides recipes for proteins. The other molecules and organelles needed to make proteins using the recipes are all over the cell. Having multiple nuclei may allow the cell to make proteins in many places in the cell.

The hard outer covering—test—of the organism may be difficult to build. Many smaller cells would have a lot more surface area and require a lot larger test. This is similar to the reason people might build a fort together instead of each family building their own fort. The organism itself doesn't usually fill all the test. It may shrink into a small area, leaving other organisms to move in. some ecologists wonder whether the xenophyophores are "farming" and eating these other organisms. If so, building a larger "farm" may provide more food.

**Learning from the Case Study**

- Why are cells usually small?
- What is a possible advantage to being one large cell?
- Why are nuclei important?

**Check Your Understanding**

- What characteristics do all living things share?
- How are prokaryotic and eukaryotic cells the same and different?

## DNA Provides Continuity and Change

DNA contains instructions for making proteins. Proteins provide the structure of the cell and regulate its activities. One analogy for an organism's complete set of DNA is a cookbook. Each recipe for a protein is called a **gene**. The individual's genetic code is its **genotype**. What the

individual is like, in terms of its anatomy, physiology, and behavior is its **phenotype**. Both genetics and the environment determine an individual's phenotype (Figure 6).

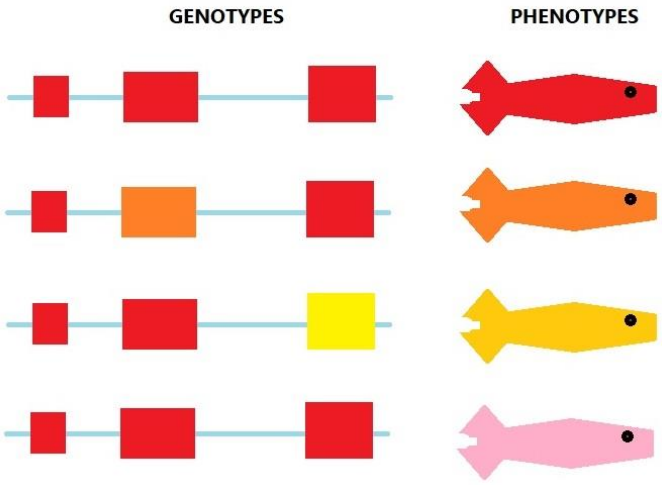
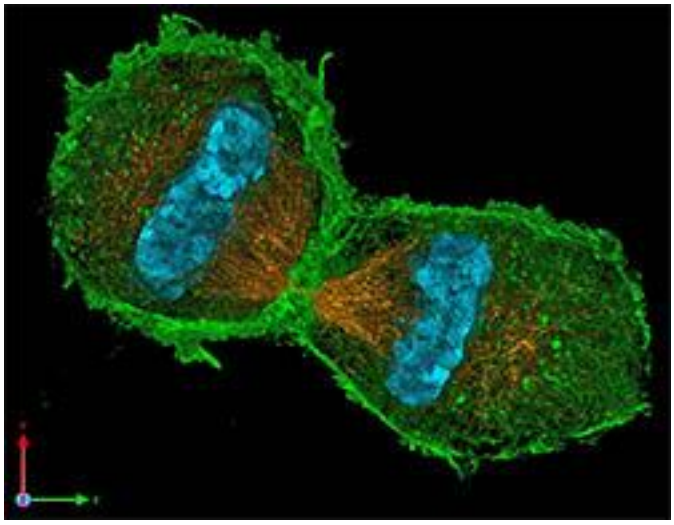



Figure 6. Schematic of how genes may differ between individuals in a population. This is genetic variation. Different genotypes can lead to different phenotypes, such as fish color. However, individuals with the same genotype may have different phenotypes. The pink and red fish have the same genotype for color, but the pink fish may have lacked the nutrients to give it a red color.

In eukaryotes, the genes are arranged into strands called **chromosomes** (See Chapter 3, Figure 22). Prokaryotes have rings instead of strands. Cells must divide to make new unicellular organisms, or allow multicellular organisms to grow, heal, and make reproductive cells (Figure7). The cell that divides is called the **mother cell** and it divides into **daughter cells**. When mother cells prepare to divide, they copy their DNA. This allows the information in one generation to be passed to the next generation. If the DNA were always copied perfectly, the next daughter cells would have exactly the same DNA as the mother cell. But the process is not perfect, so the copy is sometimes different from the original. This is a **mutation** in the DNA. A mutation in s gene will create a new **allele**—variety of the gene. Mutations may be good, bad, or neutral in any particular environment.

**Misconception Alert: Mutations happen because they are needed.**

**FALSE.** Mutations are random. Organisms do not get specific mutations by trying or because they would be helpful. Specific experiences in life do not cause specific mutations. For example, building muscles in life will not cause a mutation for larger muscles. Cutting grass for generations will not cause a mutation that results in short grass. Needing a way to survive bad conditions will not cause mutation that are helpful in those conditions. Exposure to radiation and certain chemicals can increase the frequency of mutations, but the changes are still random.



https://en.wikipedia.org/wiki/Autopoiesis#/media/File:3D-SIM-4_Anaphase_3_color.jpg

Figure 7. Late phase of division in mouse cells. The color is added for contrast. The blue material is the chromosomes. The yellow lines are the part of the cytoskeleton, which works like our muscles and bones to change the shape of the cell and the position of its contents.

Imagine that cell A had perfect copying of DNA. After many divisions all the cells in line A would be genetically identical. If the environment changed, they might all die. Imagine that cell B had mutations during DNA copying. The cells in that line would have genetic variation. Some cells might be able to survive in the new environment. Many organisms combine DNA with each other when they produce offspring. This is **sexual reproduction**, which produces offspring that are different from each other and from their parents. It can occur in both unicellular and multicellular organisms, though the processes may be different. Sexual reproduction increases genetic variation.

Multicellular organisms can usually reproduce by making specialized sex cells or **gametes**: eggs and sperm. These gametes join to from a new embryo, which will get roughly half its DNA from each parent. Each gamete is different from every other gamete, so offspring may be very different from each other. Some multicellular organisms reproduce using **asexual reproduction**, producing genetically identical offspring, but even these species usually reproduce sexually sometimes. Sexual reproduction is critical for producing variation in offspring, but it is wasteful because only a fraction of gametes get together to make embryos. It might also require a lot of time and energy to obtain a mate, though this is not true of all species. Organisms that use both asexual and sexual reproduction benefit from both variation and efficiency. Types of reproduction will be discussed more in Chapter 12.

Organisms that reproduce sexually usually get one set of chromosomes from their mother and one set from their father. The genes from one parent may be different alleles than the genes from the other parent. For example, one allele of a gene coding for pigment makes a Labrador retriever dog's fur black (Figure 8). Another allele of the same gene makes brown pigment.

Some traits are **dominant**, meaning that only one copy of the gene is necessary in for the individual to have the trait. The trait for black color is dominant in these dogs. The dog will be black if it gets the black color allele from one parent or both parents. A dog will be brown only if it gets the brown allele from both parents. Because the dog needs to have two copies of the brown allele to be brown, we say that brown is a **recessive** trait. Individuals with the dominant trait may carry a recessive allele, but you can't tell whether they are carriers by looking at them.

AI-generated image

Figure 8. Coat color in Labrador retriever dogs is controlled by multiple genes. One determines whether the coat will be black (the dominant trait) or brown (the recessive trait), which is usually called chocolate. The chocolate lab got the brown pigment allele from both parents, but the black dog may have either one allele for each pigment or two alleles for the black pigment.

**Misconception Alert: Recessive alleles are more likely to disappear.**

**FALSE.** Simply being recessive does not make an allele likely to become less common. Alleles become less common if they reduce the fitness of the individuals that carry them or if random events in small populations happen to eliminate them. Otherwise, the proportion of the different alleles stays fairly constant over generations (see **Taking It Further: Testing for Evolution with the Hardy-Weinberg Equation**).

### Check Your Understanding

- What is the role of DNA in reproduction?
- What are alleles and what process creates them?
- Name at least one advantage and one disadvantage of sexual reproduction.

## Evolution is a Change in Gene Frequency

As we have seen, mutation leads to multiple alleles of the genes and genetic variation between members of the same species. Some of these variations will turn out to be an advantage in a particular place and time, allowing certain individuals to leave more offspring than other members of their species. Biological **fitness** is a measure of an individual's reproductive success compared to other individuals of the same species in the same place. By definition, a more fit individual will leave more copies of its own DNA in the next generation, so the genes that gave it an advantage are very likely to become more common. This process is called **natural selection** (Figure 9). The key elements are genetic variation, differences in fitness under the current conditions, and changes in the proportion of specific genes.

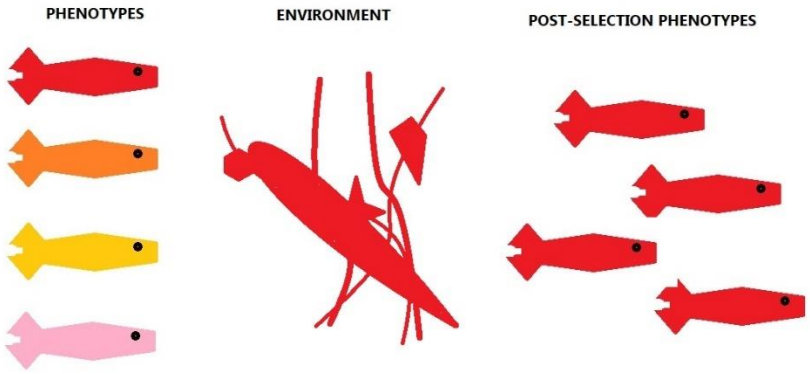



Figure 9. Natural selection in a hypothetical fish population. Individuals have heritable (genetic) differences due to random mutation. In this example, red fish can hide in the environment, so are more likely to leave offspring, which will have the genes of their parents. Over time, the proportion of the different alleles will change. In this case, we expect the frequency of alleles for red and yellow to become less common.

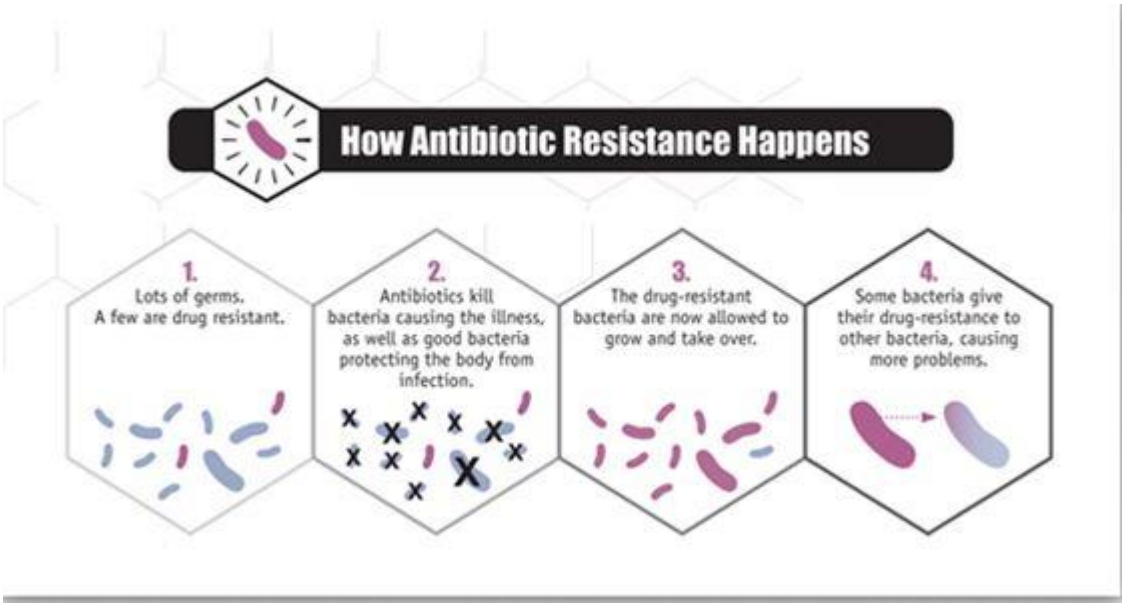
**Misconception Alert: Natural selection acts for the good of the species**

**FALSE.** Natural selection is the result of individuals leaving more offspring than other individuals of the same species. Individuals may increase their fitness in many different ways, which will vary by the species. They might invest more in their offspring, cooperate effectively, fight off disease better, be better at infecting other organisms, conserve water better, or attract better mates, for example.

The proportion of different alleles of genes is called gene frequency. Biological **evolution** is a change in gene frequency. Imagine that a plant has a mutation that makes it more resistant to a disease. It will probably leave more seeds than its neighbor of the same species. About half of

those seeds will contain the allele that increases disease resistance. If the disease is still a threat, less-resistant plants will die or reproduce less. Each generation will then have more individuals with the alleles that make the plant resistant to the disease. Because these plants are still the same species, whether they are resistant or not, this is called **microevolution**. For other examples, see **Make the Medical Connection: Natural Selection and "Superbugs"** and **Case Study Part 3: Surviving Toxins**.

**Make the Medical Connection: Natural Selection and "Superbugs"**




http://www.cdc.gov/media/dpk/2013/dpk-untreatable.html

Figure 10. Evolution of antibiotic resistance in bacteria. Individual bacteria vary in their level of resistance due to mutations in the past. Some survive a dose of antibiotics and reproduce. Others die. The resistant bacteria become more common. They can also transfer their genes to other bacteria.

Penicillin was discovered just before World War II. It was extremely effective at killing many bacteria that cause diseases in humans and other animals. Several other antibiotics were later discovered and used successfully. Unfortunately, misuse of antibiotics and widespread use of antibiotics in everything from soap to animal feed has caused selection for bacteria that are resistant to antibiotics. Now many types of disease-causing bacteria and fungi are resistant to multiple types of antibiotics. These resistant strains are estimated to cause over 2 million illnesses and 23,000 deaths a year.

**Taking It Further: Testing for Evolution with the Hardy-Weinberg Equation**

How can we tell whether gene frequencies are changing? The Hardy-Weinberg model is an equation that predicts the frequency of individuals with particular traits given certain gene frequencies. To make the model simple, imagine two alleles for a gene that codes for color in a beetle. Assume that green is dominant and brown is recessive. That means that a beetle with one allele for green (G) and one for brown (g) will be green.

The probability of an individual getting a G allele = p
The probability of an individual getting a g allele = q

The probability of two events occurring together is the product of the probability of one occurring multiplied by the probability of the other event occurring. In other words, if the probability of heads in a coin toss is 50%, the probability of flipping two heads in a row is 50% X 50%, or 25%.

In the case of genetics:

- The probability of getting a copy of G from both egg and sperm is $p^2$.
- The probability of getting a copy of q from both egg and sperm is $q^2$.
- The probability of getting a copy of G from the egg and g from the sperm is p X q
- The probability of getting a copy of g from the egg and G from the sperm is p X q

The last two probabilities can be combined because we assume it doesn't make any difference which allele comes from which parent. So the probability of getting g from one parent and G from the other parent is 2pq.

The Hardy-Weinberg equation shows these probabilities as:

$$p^2 + 2pq + q^2$$

That is, $p^2$ of the population will be GG, 2pq of the population will be Gg, and $q^2$ of the population will be gg.

We can't tell how many beetles have one G and one g because they will look just like the beetles with two G alleles. But we know how many have two g alleles because they will be brown. Imagine that 1% (or 0.01) of the population that hatches is brown (gg). The probability of g will be the square root of 0.01, or 0.1.

Any gene that is not g will be G, so 1 – q = p. In this case 1 – 0.1 = 0.9, so p = 0.9.

$p^2$ = 81%

**Continued**

**Model Skill: Testing for Evolution with the Hardy-Weinberg Equation, cont.**

Knowing the gene frequency also tells us how many individuals are heterozygous.

2pq = 18%  (Note that the total must equal 100%)

Both the GG individuals and the Gg individuals would be green, so 99% of the population (81% + 18%) would be green. This makes sense if 1% were brown.

Would the next generation of beetles have the same proportions?

They usually would if:

- No beetles are entering or leaving the population.
- There are no new mutations in the G/g gene
- No random events happen to change the proportion. This is most likely to be a factor in small populations. If very few beetles are brown, and all happen to be killed in a storm, the gene frequency would be changed a lot. In large populations, this is less likely to be an issue.
- Beetles are mating randomly
- There is no advantage or disadvantage to having any of the three patterns (GG, Gg, or gg)

The last issues are often the most interesting. What happens if being brown is a disadvantage, for example? We would expect to see fewer of the brown beetles than the model predicts. This would mean the population would not be in equilibrium. We could track this from hatching to adulthood or generation to generation. Changes from the predictions of the Hardy-Weinberg model show evolution—a change in gene frequencies over time. Using the model, we can even calculate the fitness advantage of having a particular allele by comparing the expected values to the actual values.

**Misconception Alert: Evolution has a goal or is perfecting organisms**

**FALSE.** Evolution is a change in the proportion of alleles. It is a result of natural selection and random events. Genetic traits that increase fitness in one time or place may decrease fitness in other circumstances, so there is no “perfect” organism.

**Case Study Part 3: Surviving Toxins**

http://www.photolib.noaa.gov/htmls/expl2234.htm

Figure 11. Xenophyophore in the claw of a deep sea exploring instrument. These organisms rarely survive outside their natural environment but seem immune to some toxic metals.

Chemicals such as lead, uranium and mercury are usually deadly in small doses, but xenophyophores can accumulate large concentrations without any apparent harm. How could this ability evolve?

Imagine the landscape of the ocean floor. It will be very different in different places. Xenophyophores are usually found where a lot of organic material is either falling from the upper areas or flowing up from below the ocean floor. This provides more of the particles that the organisms consume. Some areas will also have higher concentrations of toxins than others. These may be the same places that have good food supplies for xenophyophores because the toxins might be carried in with the sediments.

The individual xenophyophores would have different abilities to deal with the toxins due to random mutation. Those that could live in the areas that had a lot of toxins would have less competition from other individuals and may also be able to live in places with more nutrient inputs. They would tend to leave more offspring than other individuals. An occasional random mutation in their offspring might lead to even greater ability to survive high levels of toxins.

**Learning from the Case Study**

- Did the organism get mutations for dealing with heavy metals because it needed them?
- Did the organism get mutations for dealing with heavy metals by trying?
- Did one individual learn to deal with heavy metals and pass the learning on when it divided?

Evolution can happen without natural selection. Genes can enter a population from other populations (Figure 12). An allele created by a mutation in one population could be carried to a new population if individuals, seeds, or pollen were carried there. A gene could then spread in the population.

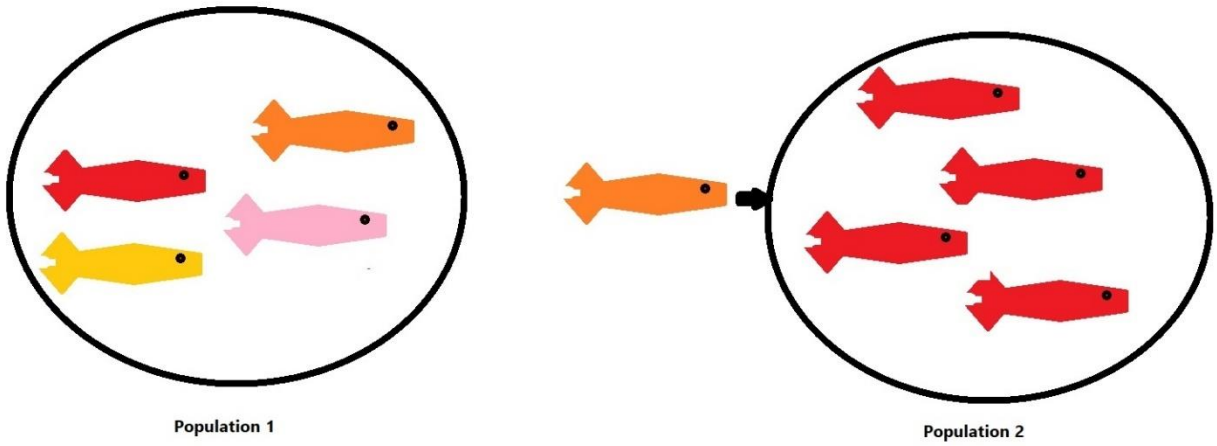



Figure 12. Gene flow happens when individuals move between populations. In this example, the frequency of the allele for orange color will increase in Population 2 when an orange individual joins it and begins breeding.

If populations are small, the proportion of alleles can change due to random events. Imagine that only a few individuals had that variety of gene. If they all happened to die or failed to breed, that allele would be lost. This is called genetic drift (Figure 13). Genetic drift can also happen when a lot of a population dies for some reason. The part of the population that survives this "bottleneck" event may have different gene frequencies than the original population had.

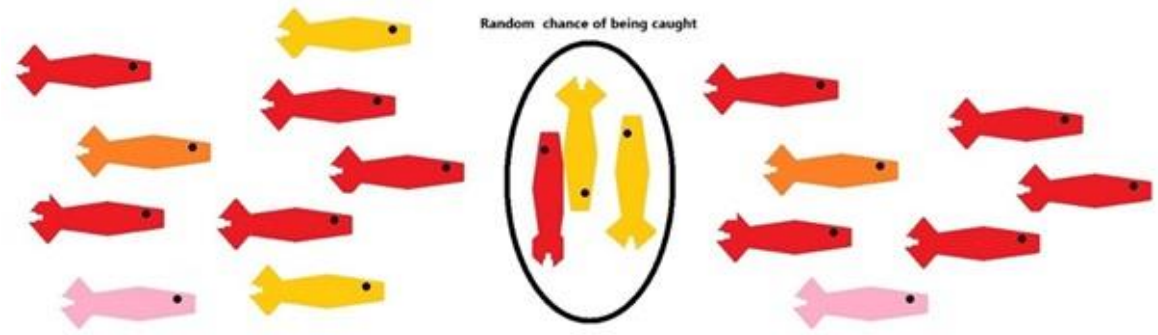



Figure 13. Genetic drift happens in small population when random events change the proportion of genes. The example pictured here is extreme, but a natural disaster might kill several individuals in a small population and wipe out a rare allele. In this example all the yellow fish happened to be caught. If yellow color is a dominant trait, the allele for yellow color disappears from the population.

**Check Your Understanding**

- What are the key elements of natural selection?
- How can gene frequencies change in a population without natural selection?
- Why are random changes in gene frequency more likely in small populations?

**Macroevolution creates new species**

A species is a group of individuals that can potentially interbreed but cannot breed with members of other groups. This might seem like a tidy definition, but it becomes complicated because species that are closely related may look very different, but still be able to interbreed under specific circumstances. The concept is also not very useful with unicellular organisms. There may be some disagreement about whether two closely related groups are members of the same species with some local variation (subspecies) or distinct species. Sometimes biologists do not know that similar-looking organisms are actually different species (see **Why It Matters: Cryptic Species**).

**Why It Matters: Cryptic Species**

**A** **B**

https://commons.wikimedia.org/wiki/File:Bombus_sporadicus_02.jpg
https://commons.wikimedia.org/wiki/File:Bombus_cryptarum_hann.jpg

Figure 14. Two cryptic species of domestic bumblebees: **A**. *Bombus sporadicus* and **B**. *B. cryptarum*. Genetic analysis was used to identify these species. Although they may look the same to us, they do not breed with each other.

The first step in managing a species is identifying it. Sometimes this is not as obvious. Species that are genetically different can look so much alike that they are classified as the same species until more evidence is analyzed. These are called cryptic—hidden—species. Sometimes the cryptic species are not even each other's closest relatives. Genetic analysis is used now to supplement the traditional types of information used to determine species. There is no magic threshold for saying that two groups that show genetic differences are two separate species. The judgment of experts is still required.

Bumblebees are critical pollinators for many valuable food crops. The bees are often transported a long way by professional beekeepers who are paid for the bees' pollinating services. Their numbers are declining for mysterious reasons. Conserving the bees probably requires telling them apart, but many species look alike until their DNA is examined.

- Should government agencies research bee species and their conservation?
- Why might there be political controversy about classifying a particular group as a separate species, especially if it might be endangered?

**Macroevolution** happens when evolutionary changes result in new species. Macroevolution can happen over a long period of time as populations that are isolated from each other become more and more genetically different due to chance and the demands of different environments (Figure 15). Macroevolution can even be rapid due to dramatic genetic changes.

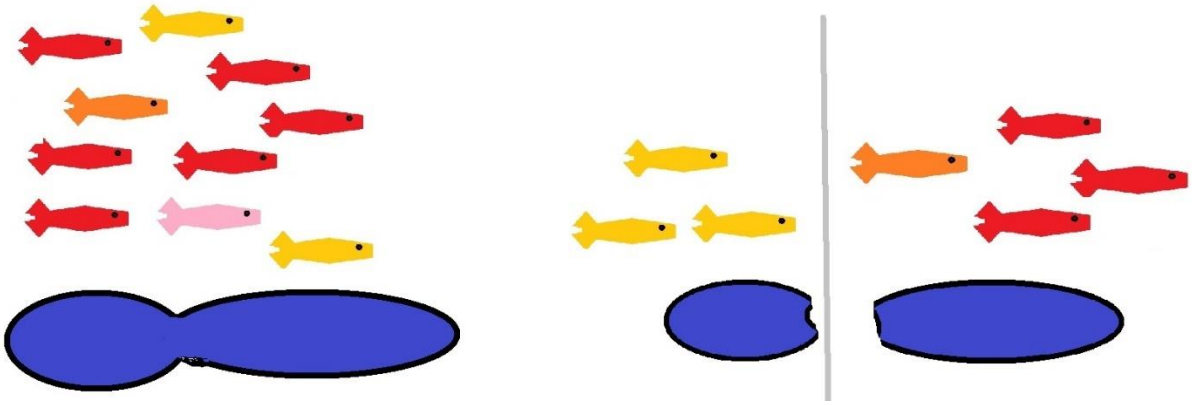
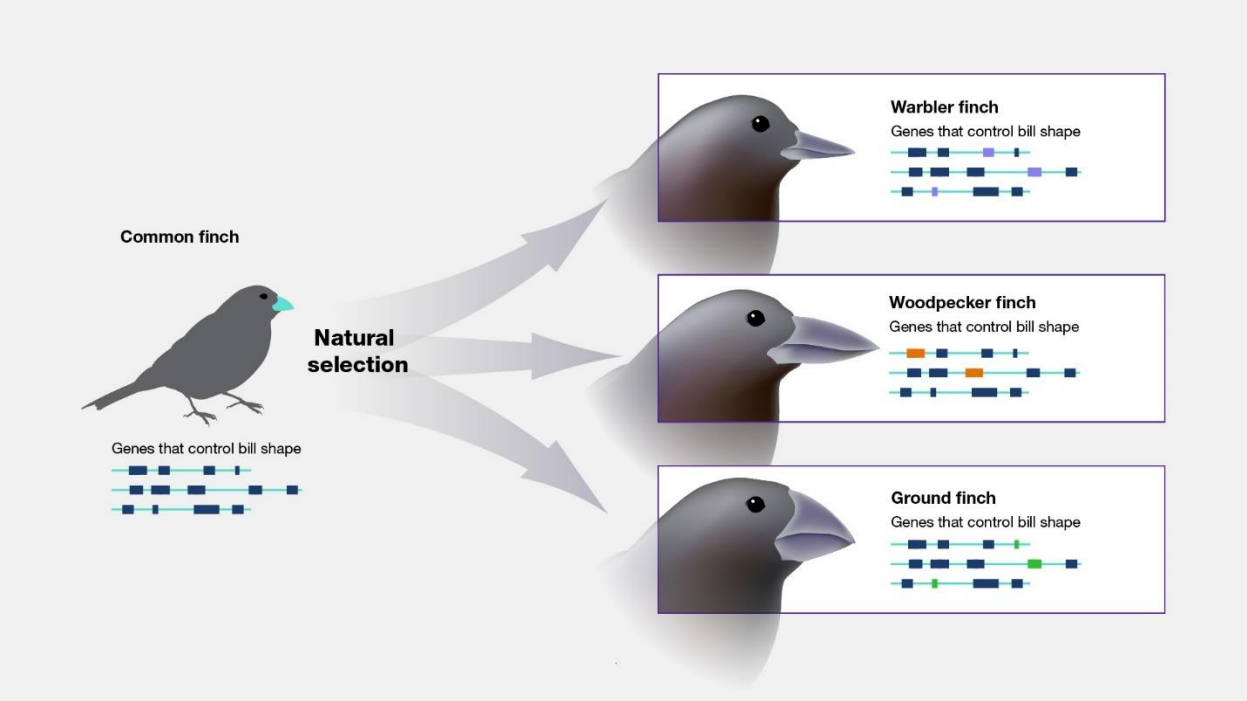


Figure 15. Macroevolution can happen if a population is split into isolated populations. The original population was divided when a changing climate separated one lake into two. Each of these new populations changed in different ways over time, due to different environmental pressures, random mutation, or both. Eventually, they may be unable to breed with each other due to genetic differences, even if the lakes are connected again. That would mean macroevolution had occurred.

**Analyze the Figure**

- Was there variation in the original population?
- Is there variation within each of the populations of the two different species?

When we look at the genotypes and phenotypes of species, we can see how genetic changes have led to the phenotypic changes. For example, the common finch has close relatives with bills that are phenotypically different. Bill shape is a trait that can determine success in feeding, depending on factors such as the size and type of food available and the competition for different food types. For example, in an environment where only large, hard seeds are available, individuals with alleles for large strong bills will leave more offspring. We can now identify specific alleles that cause variation in bill shape (Figure 16).




https://www.genome.gov/genetics-glossary/Evolution

Figure 16. Variation in finch bills as a result of natural selection.

**Analyze the Figure**

- Are the genes that control bill shape in the same locations for all the species?
- Are some of the alleles the same for all the species?
- About how many of the loci have different alleles for bill shape in these species?

**Organisms are Categorized by Evolutionary Relationships**

It would be nearly impossible to study all the species on Earth without organizing them efficiently. Look at the animal in Figure 17. What would you call it? There are many common names for this species. You might call it a cougar, a panther, a cat-a-mount, a painter, an American ghost, a puma, or a mountain lion. Some species present the opposite problem. There are many different species of mice, but most people only have one common name for them. Each living thing is given a unique scientific name to avoid this confusion. *Puma concolor* is the scientific name for this big cat. The scientific name is composed of the genus name followed by its specific or trivial name. All over the world, scientists use the same words for the scientific names of species and other categories of living things.

https://www.nps.gov/jeca/learn/nature/mountain-lion-puma-concolor.htm

Figure 17. *Puma concolor*, a member of the cat family, Felidae.

All scientific names are Latinized, meaning that they are either Latin or follow some Latin grammar rules. Scientific names are always underlined or italicized. The genus is always capitalized. The specific or trivial part of the name is not. The genus can be used separately. For example, you might say that the members of the genus *Puma* can roar. Species may share the same same specific or trivial name, so this is never used by itself to describe a species. For example, *concolor* means that something is all the same color. *Puma concolor* is a species of big cat. *Abies concolor* is a white fir tree. You may see this cat's name written as *P. concolor* if its full name has been given already.

Species are categorized into larger groups that have common ancestors. When the first classification systems were invented, scientists relied on the appearance of organisms to figure out relationships. DNA analysis and the fossil record now provide much more information.

**Model Skill: Phylogenetic Trees**

Phylogenetic trees show evolutionary relatedness between groups. These are arranged so that branching points show a split of ancestral species into new species (Figure 18). For example, the two species of right whale are descendants of the same species (now extinct). The original species spread into northern and southern groups that became separated. Over time, the isolated groups became different enough to become separate species. This is an example of macroevolution.

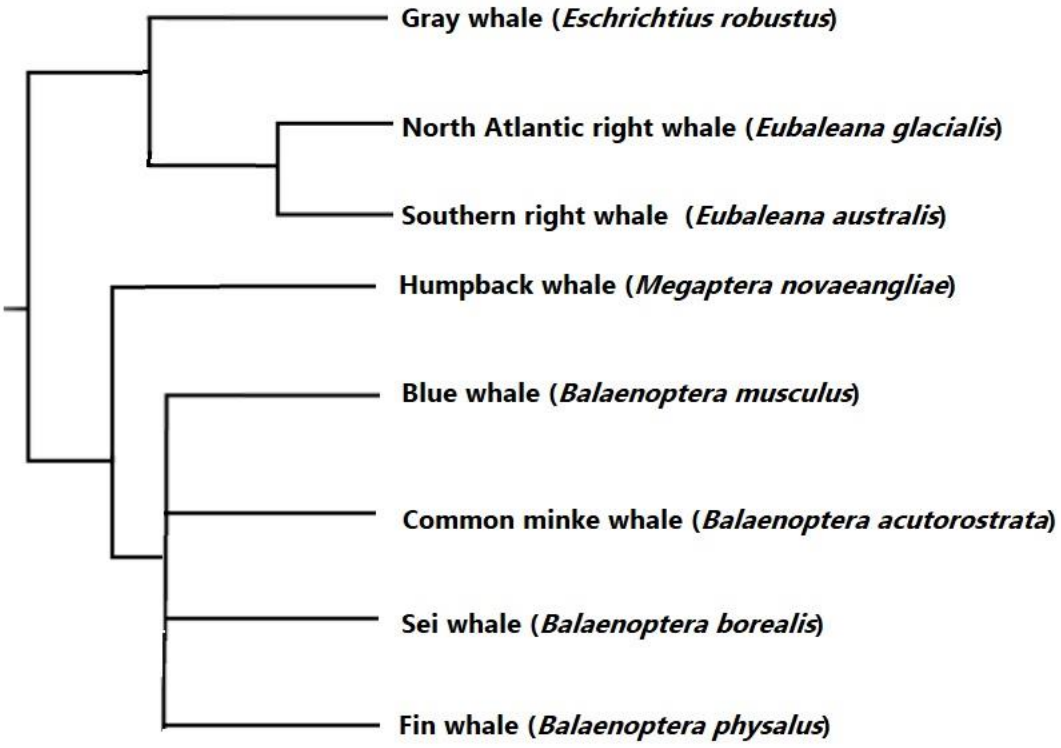



Figure 18. Phylogenetic tree based on DNA analysis showing evolutionary relationships between some whale species. Branching points indicate that an ancestral species split into new species. Based on data from: Collier, M., Mann, J., Ali, S., & Bansal, S. (2022). Impacts of human disturbance in marine mammals: Do behavioral changes translate to disease consequences?. In *Marine mammals: the evolving human factor* (pp. 277-305). Cham: Springer International Publishing.

All of the members of the genus *Balaenoptera* are in the same grouping because taxonomy should reflect evolutionary history. The humpback whale is more closely related to the fin whale than the southern right whale. The diagram does not show whether the fin whale is more closely related to the sei whale or the blue whale because relatedness is only shown by splitting of the lines, not the distance between the names of species. If you flipped the names of the sei whale and the blue whale, the diagram would be equally accurate.

The phylogenetic tree of the family Felidae shows how *Puma concolor* (Figure 19) is related to other cat species (For an explanation of how to read these, see **Model Skill: Phylogenetic Trees**). Its closest relative, the jaguarundi, belongs to the same genus. The group that includes lions and jaguars diverged from the puma lineage about 10.8 million years ago.
For another example of how these models can be useful, see **Evolutionary Perspectives: Animal Models and Toxicity Tests**.

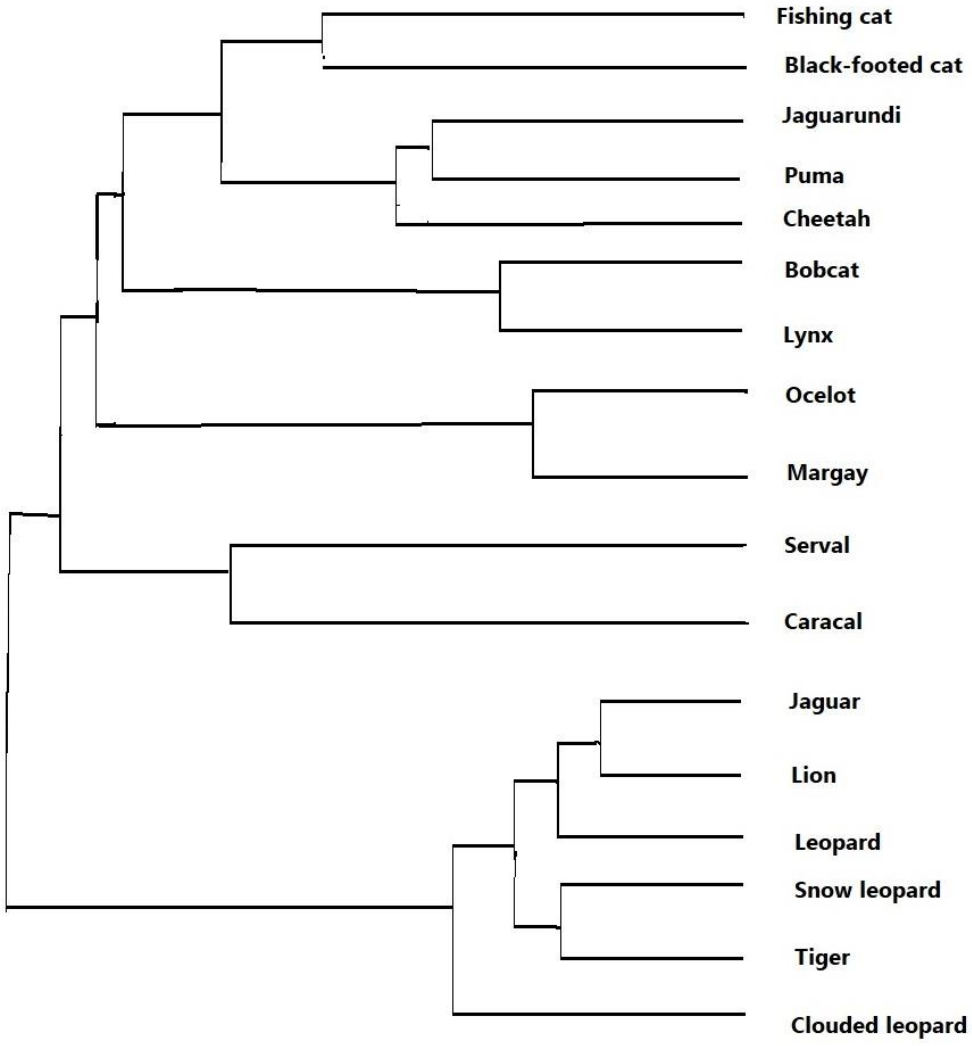



Figure 19. Evolutionary relationships of selected felines. Adapted from: O'Brien, S. J., Johnson, W., Driscoll, C., Pontius, J., Pecon-Slattery, J., & Menotti-Raymond, M. (2008). State of cat genomics. *Trends in genetics*, *24*(6), 268-279.

**Analyze the Figure**

- Is the cheetah more closely related to the jaguarundi or to the bobcat?
- Are snow leopards more closely related to leopards or tigers?

You may have heard of **hybrids** born in zoos from the mating of lions and tigers (see ligers https://en.wikipedia.org/wiki/Liger#/media/File:Liger_couple.jpg and tigons https://en.wikipedia.org/wiki/Tigon#/media/File:Tigon4.jpg). Because lions and tigers only split off from their common ancestor a few million years ago (see Figure 19), they are still similar enough to interbreed. They don't interbreed in the wild and are clearly very different, so they are still considered separate species. There are many examples of hybrids born to species in the same genus, but they are almost always the result of mating in captivity or because a species has been introduced to an environment with a close relative.

**Hypothesis Testing: How Did Hybridization Lead to New Sunflower Species?**

Mules are an example of a sterile hybrid that results from crossing a male donkey (*Equus asinus*; 62 chromosomes) and a female horse (*Equus caballus*; 64 chromosomes). Mules (*Equus caballus* X *asinus*) have an odd number of chromosomes (63), so they cannot form viable eggs or sperm. In other species, parents have the same number of chromosomes, leading to hybrids that can breed with each other and the parental species. If there is reproductive isolation between the hybrids and parental species, eventually, the hybrids may change so much that they are a separate species. This is an example of hybrid speciation—a new species resulting from interbreeding of two other species. But what keeps the hybrids separate enough that they become a new species? To answer this question, ecologists must use observations from the present to infer what happened in the evolutionary past of the species.

Sunflower species (*Helianthus* spp.) grow throughout the continental United States. Two species have hybridized and produced three hybrid species (Figures 20 and 21). Each species has the same number of chromosomes. The three hybrid species are found in different habitats. *H. anomalus* is found in sand dunes. *H. deserticola* is found on the desert floor. *H. paradoxus* is found in salt marshes.

USDA Photo

NPS Photo

USDA Photo

NPS Photo

https://plants.sc.egov.usda.gov/home/plantProfile?symbol=HEAN3, https://www.fs.usda.gov/wildflowers/plant-of-the-week/images/commonsunflower/Helianthus-annuus-12B.jpg, https://www.nps.gov/arch/learn/nature/asteraceae_helianthus_petiolaris.htm

Figure 20. *Helianthus annus* (left) and *Helianthus petiolaris* (right).

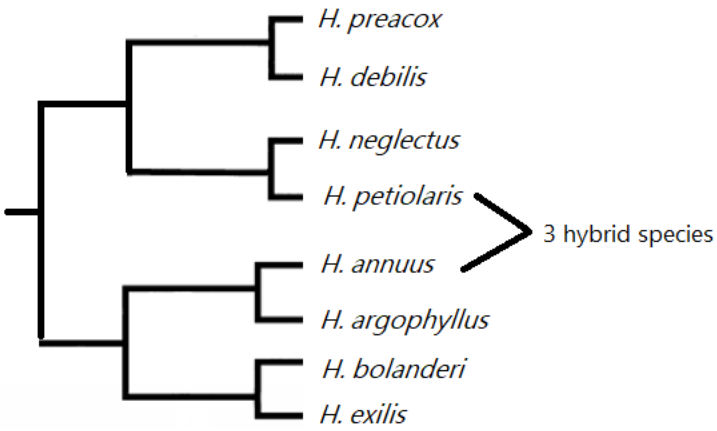



Figure 21. Cladogram for the genus *Helianthus* based on genetic information. The three hybrid species are on the far right. Modified from: Rieseberg, L. H. (2006). Hybrid speciation in wild sunflowers 1. *Annals of the Missouri Botanical Garden*, *93*(1), 34-48.

Rieseberg (2006) investigated 3 hypotheses about how hybrid speciation may have happened in these sunflowers.

Hypothesis 1: Hybrid speciation in the sunflower species happened due to physical changes in chromosomes, leading to greater *reproductive isolation* from members of parent species.

Hypothesis 2: Hybrid speciation in the sunflower species happened due to hybrids colonizing a new area, leading to *geographical isolation* of the hybrids from the parent species.

Hypothesis 3: Hybrid speciation in the sunflower species happened due to hybrids colonizing a new type of habitat or niche, leading to *ecological isolation* of the hybrids from the parent species.

Rieseberg's team used computer simulations to see what events were most likely to lead to hybrids becoming separate species. The simulations assumed that a new habitat was available and that the hybrids had a higher fitness in the habitat than the parent species. If the hybrids had a strong advantage in new, open habitats, hybrid speciation did occur, but another outcome was much more common. When hybrids and parent species interbreed, useful alleles can be transmitted from one parent species to the other. In the simulations, this often led to one of the parent species taking over the novel habitat from the hybrids before any new hybrid species could become established. Does this finding support or refute any of the hypotheses?

In simulations with less spatial or ecological separation for the hybrids, hybrid speciation was rare and usually involved one of the parental species going extinct. Hybrid speciation was more likely when they were more reproductively compatible with parent species. Which of the hypotheses are supported or refuted by the simulation findings?

The two parental species often occur in the same general area, but in different soil types, which means that they may be spatially and ecologically separated. Each of the three hybrids occurs in the same general area as parental species, but specializes on different extreme habitats, some of which are found only in small areas.

Rieseberg found many genetic differences between each of the five species of sunflower. Changes like this would usually lead to the species being reproductively incompatible. This was directly investigated by creating crosses between the species and testing reproductive compatibility (Figure 22).

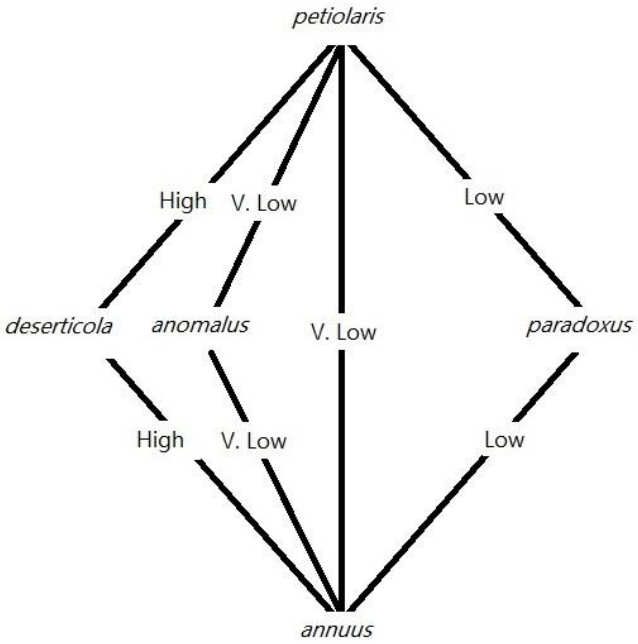



Figure 22. Diagram showing ability to hybridize between selected sunflower species. *H. petiolaris* and *H. annuus* are the parental species. Modified from: Rieseberg, L. H. (2006). Hybrid speciation in wild sunflowers 1. *Annals of the Missouri Botanical Garden*, *93*(1), 34-48.

**Analyze the Figure**

- Do the parental species (*H. annuus* and *H. petiolaris*) seem to be very reproductively compatible? Explain your answer.
- Do all or some the hybrid species seem to be reproductively isolated from the parental species? Explain your answer.
- Which hypotheses do the fertility experiments support or refute?

**Evaluate the Hypotheses**

- Can any of the hypotheses be eliminated based on the data presented here?
- Are any or all of the hypotheses supported by the data presented here? Explain your reasoning.

**Evolutionary Perspectives: Animal Models and Toxicity Tests**

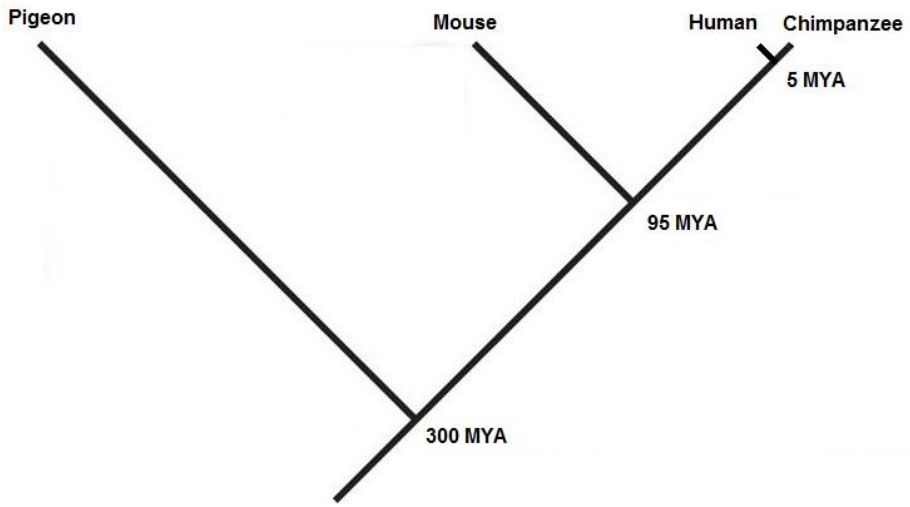



Figure 23. Evolutionary relationships between selected animals. “MYA” means “million years ago,” an estimate of when the lines separated.

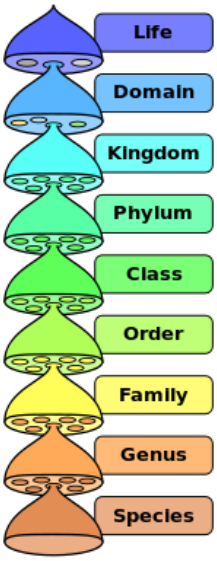
Suppose you wanted to know whether a certain substance is dangerous to humans. You might find that some people who had a high level of substance X in their drinking water also had a higher risk of a particular cancer. Unfortunately, this is not a controlled study. If the people shared a water source, maybe they shared other factors that increased their cancer risk.

Another approach is to test the substance on non-human animals. This allows researchers to conduct controlled tests on large samples. The question then becomes whether our bodies respond in the same way to the same substance. What determines how similar we are to other species? A major factor is how closely related we are. Figure 23 shows that chimpanzees are our closest living relatives. So we would expect human physiology to be more similar to chimpanzee physiology than to mouse physiology. But chimpanzees are very expensive to keep. Chimps also live a long time, so it might take decades to see the changes that could be seen in a two-year-old mouse. There is also a lot of public resistance to chimpanzees being used for health research. For these reasons, mice are often used in studies when we are really interested in humans.

Researchers must make a tradeoff between using the species most similar to humans and the species that are most practical to study. Toxicity studies on mice and other non-human animals have flaws, but if we do not use non-animal models to decide how to regulate substances, we have no way to test potential toxins before humans are exposed to them.

The groups of living things are arranged in a hierarchy. Think of each level as a box that has smaller boxes inside it. Each of those boxes contains smaller boxes, and so on. Every box fits in only one larger box. This is also referred to as a nested set (Figure 24). For example, all members of the genus *Canis* belong to the family Canidae. All members of the family Canidae belong to the order Carnivora. All members of the order Carnivora belong to the class Mammalia. All members of the class Mammalia belong to the phylum Chordata. All members of the kingdom Animalia belong to the domain Eukaryota.

**A**




http://en.wikipedia.org/wiki/Genus

**B**

Example of Classification: Wolf

Domain: Eukaryota
Kingdom: Animalia
Phylum: Chordata
Class: Mammalia
Order: Carnivora
Family: Canidae
Genus: *Canis*
Species: *Canis lupus*

Figure 24. Hierarchy of biological classification. Right: Overview showing that the sets fit completely inside the next higher level. Each larger group can contain multiple smaller groups. Left: Example showing how the wolf would be classified.

**Analyze the Figure**

- Which group is larger, family or order?
- Can members of the same class be in different phyla (the plural of phylum)?

If this is a bit confusing, think about classifying your location. You can be in a classroom, in a building, and on a campus all at the same time. If you and a friend are both members of the same smaller set (classroom) you must both be members of the same larger sets (building and campus). But you could be members of the same larger sets (building and campus) but be in different smaller sets (different classrooms).

In the same way, a species can be a member of the family Canidae (larger set) and not belong to the genus *Canis* (smaller set), but if it belongs to the genus *Canis* (smaller set), it must belong to the family Canidae (larger set). For example, all members of the genus *Vulpes* are

also members of family Canidae (Figure 25). Explore this with species that interest you in: **Do Try this at Home: Classification**.

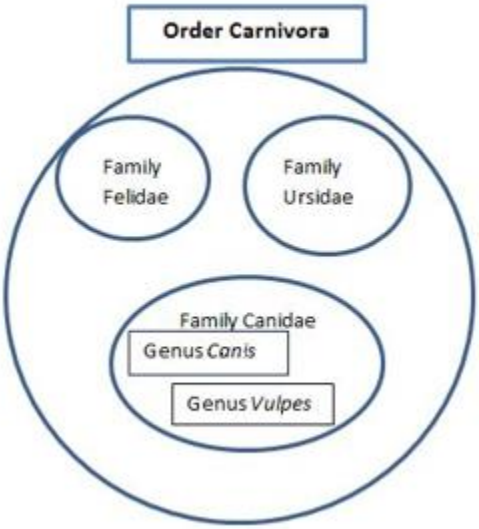



Figure 25. Simplified example of the hierarchy of biological classification starting with the order Carnivora. Carnivora contains several families, three of which are shown here. The family Canidae contains multiple genera (the plural of genus), two of which are shown here.

**Analyze the Figure**

- Which is larger a family or an order?
- Can a species be in the family Felidae and the family Ursidae?

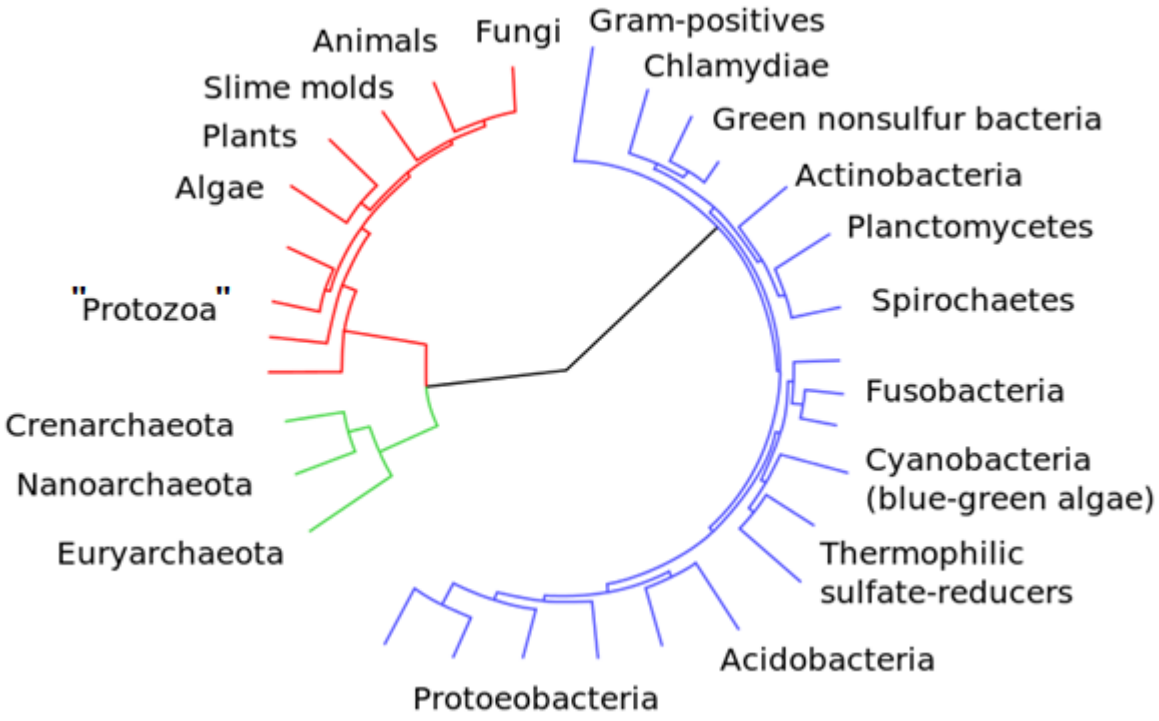
**Do Try this at Home: Classification**

Think about your favorite living thing. Make some predictions about its closest relatives. Visit http://www.itis.gov/. Do a quick search on the common name, then click on the hyperlinked name to see the taxonomic hierarchy.

Were you correct about where it fits in the tree of life? Are there species that you thought would be close relatives but are not? Are there species that seem very different, but are close relatives? Why might they look very different from each other?

Organisms are divided into 3 domains: Eubacteria, Archaea, and Eukaryota (Figure 26). Eukaryota contains the eukaryotic organisms (plants, animals, fungi, and “protozoa”). All other

organisms are prokaryotic. Figure 3 shows a comparison of prokaryotic and eukaryotic cells. The group called “protozoa” in the diagram is actually composed of multiple kingdoms. Researchers are currently creating a new system for classifying these organisms. For more on this topic, see **Case Study Part 3: Where do they belong?**




Modified from: http://commons.wikimedia.org/wiki/File:CollapsedtreeLabels-simplified.svg

Figure 26. Simplified phylogenetic tree of life. This tree is based on the same logic as the others in this chapter, it is just curved. Each color is a different domain. Blue branches are Eubacteria and green branches are Archaea. Both are prokaryotic. The branches in red are the domain Eukaryota. “Protozoa” is a convenient category but is not a technically valid one.

**Analyze the Figure**

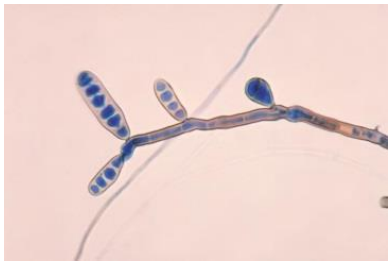
- Are animals more closely related to plants or fungi?
- Are Archaea more closely related to Eubacteria or Protozoa?
- Are “blue-green algae” (Cyanobacteria) really algae?

Some eukaryotes, such as animals and plants, are multicellular (Table 1). The kingdom Plantae is composed of multicellular organisms that get their energy from photosynthesis. The kingdom Animalia is composed of multicellular organisms that move at some stage of their lives and get their energy from eating. Algae and fungi can be unicellular or multicellular. Algae perform photosynthesis. Fungi absorb “food” over their surface and have cell walls. The cells have specific shapes and structures depending on their function (Figure 27).

Table 1. Simplified summary of eukaryotic kingdoms.

| **Kingdom** | **Cell Structure** | **Energy Source** | **Examples** |
|---|---|---|---|
| Algae | Unicellular or multicellular<br>Wall of cellulose | Photosynthesis<br>(some absorb) | Seaweed, diatoms, green algae |
| Animalia | Multicellular<br>No cell wall | Eating | Sponges, worms, insects, fish, birds |
| Fungi | Unicellular or multicellular<br>Wall of chitin | Absorbing | Yeast, mold, mushrooms |
| Plantae | Multicellular<br>Wall of cellulose | Photosynthesis | Trees, grasses, herbs, shrubs |
| Protozoa or Protista<br>(This category is undergoing major changes.) | Unicellular, some colonies | Photosynthesis, eating, or absorbing | Amoebas, paramecia, Euglena |

**A**



http://commons.wikimedia.org/wiki/File:The_fine_branching_tubes_of_the_fungus_Exserohilum_rostratum_PHIL_3784_lores.jpg

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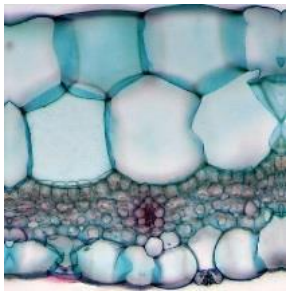
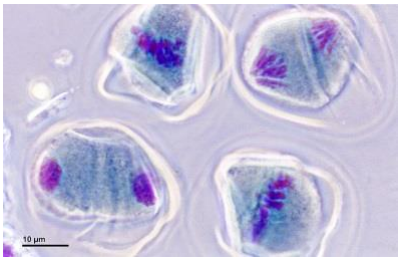


http://commons.wikimedia.org/wiki/File:Tradescantia,_leaf,_Etzold_green_2.JPG

**C**

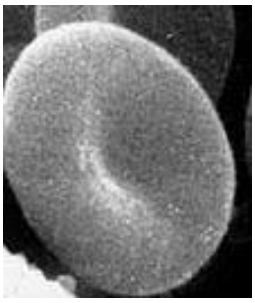
http://commons.wikimedia.org/wiki/File:Chief_cells.png

**D**



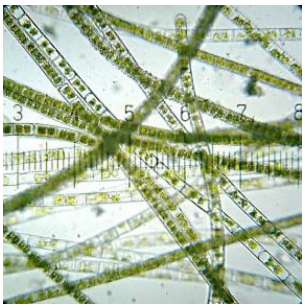
http://commons.wikimedia.org/wiki/File:Meiosis_%28261_36%29-_Dividing_pollen_mother_cells_M_I,_A_I,_T_I_%28metaphase_I,_anaphase_I,_telophase_I%29_-_Lilium_plant.jpg

**E**



http://commons.wikimedia.org/wiki/File:SEM_blood_cells.jpg

**F**



http://commons.wikimedia.org/wiki/File:20110331_012556_Algae.jpg

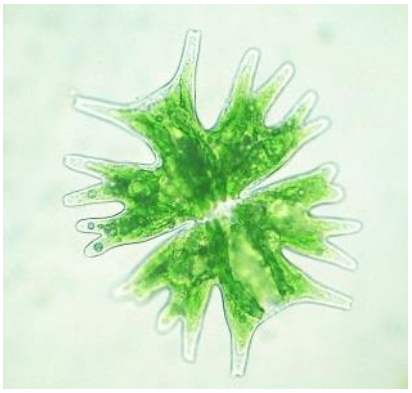
Figure 27. Examples of Eukaryotic cells from multicellular organisms. **A** Fungus that attacks human tissues, stained to show nuclei in blue. **B** Various leaf cells, stained. **C** Stomach cell from an animal stained to show the nucleus (dark circle in the center). **D** Four pollen cells dividing. Cells are stained to show the chromosomes containing the DNA in purple. **E** Red blood cell (electron microscope image). **F** Algae cells can form long filaments.

Other eukaryotic organisms, such as protozoa, some algae, and yeast (a fungus) are unicellular. These organisms live in many different places, and have many different ways of getting energy and nutrients, so their cells are also very different (Figure 28).

**A**

http://www.bbc.co.uk/education/guides/zfydmp3/revision

**B**



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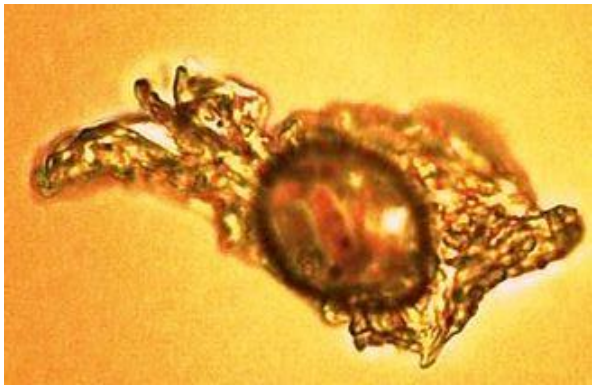
**C**



http://commons.wikimedia.org/wiki/File:Ameoba_Under_Light_Microscope.jpg

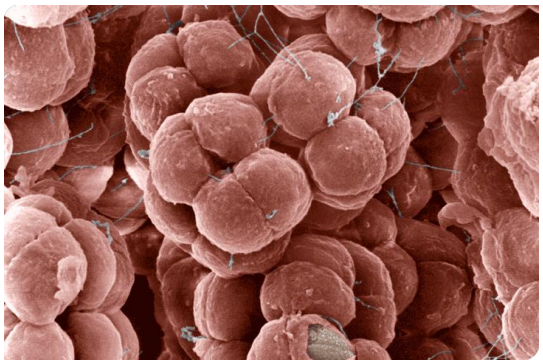
**D**

http://commons.wikimedia.org/wiki/File:Euglena_viridis.jpg

Figure 28. Microscope photos of some Eukaryotic unicellular organisms. **A** Yeast (fungus) cells used in making beer. Some are budding off smaller yeast cells. **B** Micrasterias, a freshwater algae. **C** Amoeba, a protozoan predator. The dark circle is the membrane of the nucleus. **D** Euglena, a protozoan that can do photosynthesis or eat.

Eubacteria and Archaea (which were considered bacteria until recently) are prokaryotic (Figure 29). You may be surprised that familiar groups such as animals and plants are such small branches on the tree of life. As new technology is developed, our understanding of microbes (organisms that require a microscope for us to see them) is increasing rapidly, but we still know very little about them compared to our knowledge of larger organisms.

**A**

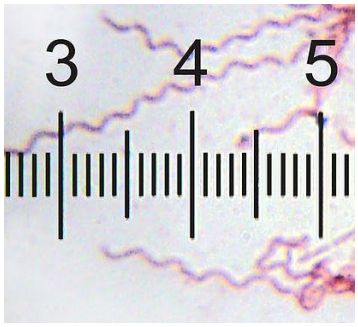


http://www.microbiologyonline.org.uk/about-microbiology/introducing-microbes/archaea

**B**

http://en.wikipedia.org/wiki/Archaea#/media/File:Morning-Glory_Hotspring.jpg

**C**

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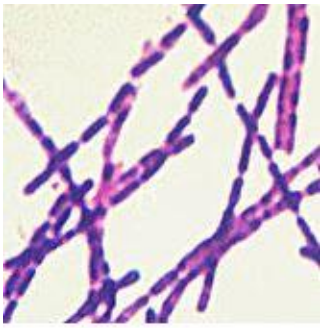
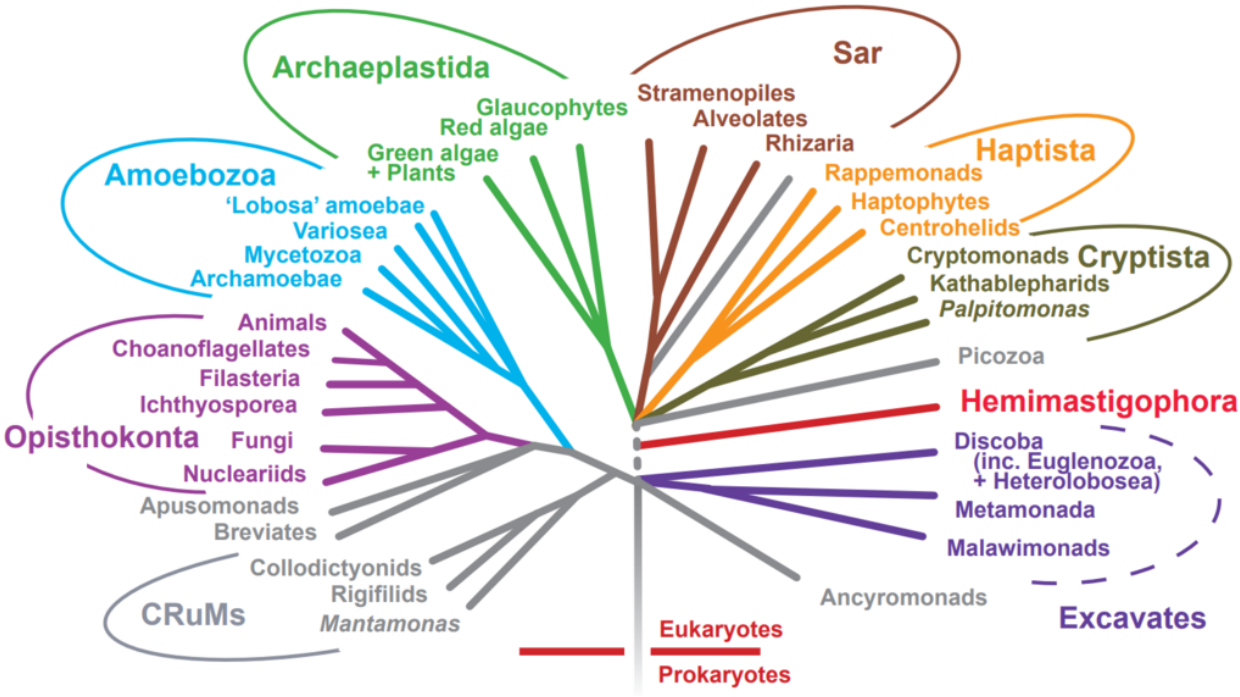


http://commons.wikimedia.org/wiki/File:Bacillus_anthracis_Gram.jpg

Figure 29. Examples of prokaryotic cells. **A** Microbe of the domain Archaea. It can live in extremely salty water. The electron microscope image has been colored. **B** Microbes from the domain Archaea that survive extremely hot temperatures provide the color in this thermal pool in Yellowstone National Park. **C** Microscope image of eubacteria from a gutter, stained. Each line on the measuring tool is one micron (µm). These bacteria are a form called spirochetes because of their long, corkscrew shape. **D** Microscope image of multiple cells of the bacterium that causes anthrax, stained. Note that the bacteria form chains.

**Case Study Part 4: Where do they belong?**




By Alastair Simpson - Dalhousie University, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=106553315

Figure 30. The Eukaryotes are split into several groups. Under this system, xenophyophores may be classified in the group Rhizaria (shown in brown), along with the foraminiferans—other eukaryotic, unicellular organisms that eat and have hard tests covering them.

The groupings that scientists use to organize the diversity of life are hypotheses about evolutionary relationships. As new information is discovered, the groupings are changed to better fit the data. When xenophyophores were first discovered, they were put in the same category as foraminiferans, amoeba-like protozoans that also have tests. Later, they were categorized with the sponges, animals that filter particles out of the water. Each cell in a sponge engulfs the food particles the same way that xenophyophores and amoebas do.

For a long time, there were only two kingdoms: plants and animals. Organisms that moved and ate were placed in the kingdom Animalia. Later, unicellular eukaryotes were categorized as Protists. As scientists learned more about these organisms, they saw that the Kingdom Protista did not fit the data. A new system might put amoeba-like eukaryotes in a group called Rhizaria (Figure 30). This would place xenophyophores with the foraminiferans again.

**Learning from the Case Study**

- What characteristics might have made early scientists think xenophyophores were animals?
- What characteristic made later scientists move them out of the animal kingdom?
- Why might classification systems change over time?

**Check Your Understanding**

- What is a species?
- How are species classified?
- Describe how macroevolution can lead to speciation.

# Key Concepts

- Living things are made of cells with DNA, require energy and specific molecules, produce wastes, respond to the environment, maintain relatively stable internal environments, grow, and reproduce.
- DNA controls activities in cells. It is passed from one generation to the next, but can be changed by mutation, producing variation between individuals.
- Some individuals produce proportionately more offspring. The genes of these individuals will tend to become more common in populations. This is called evolution due to natural selection.
- Organisms are classified according to their evolutionary relationships in a hierarchical system that can be shown in phylogenetic trees.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately identify characteristics of living things*
2. *Explain basic nature of cells*
3. *Correlate DNA function with the continuity and diversity of life.*
4. *Correctly apply the concepts of evolution by natural selection*
5. *Correctly apply concepts of classification of living things*

1. Is fire a living thing? Discuss the characteristics of living things and identify any that it has or lacks.
   *(Learning Outcome 1)*

2. Examine the phylogenetic tree in Figure 31.

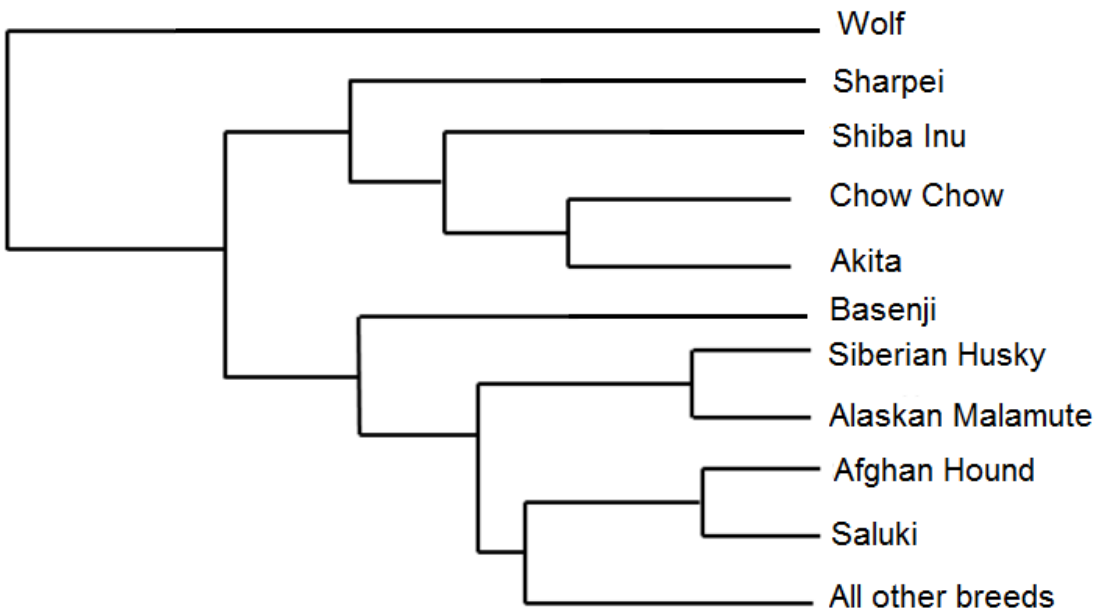



Figure 31. Phylogenetic tree of dog breeds based on genetic analysis. Of the breeds examined, only those listed showed a clear separation. Modified from: Parker, H.G., Kim, L.V., Sutter, N.B., Carlson, S., Lorentzen, T.D., Malek, T.B., Johnson, G.S., DeFrance, H.B., Ostrander, E.A. & Kruglyak, L. (2004). Genetic structure of the purebred domestic dog. *Science*, *304*(5674), 1160-1164.

A. Which breed is more closely related to akitas; basenjis or shiba inus?
B. Which pair of breeds is more closely related; huskies/malamutes or akitas/chow chows?
C. Discuss whether wolves and dogs belong to the same species. Give evidence for both sides of the argument.

*(Learning Outcomes 4 and 5)*

3. Why is the cell essential for life? Think about how a cell makes the major attributes of life possible.

*(Learning Outcome 2)*

4. A. Why is it important for DNA to be passed from one generation to the next?
B. How can mutation decrease an organism's fitness?
C. How can mutation increase an organism's fitness?

*(Learning Outcomes 3 and 4)*

5. Suppose that a plant species grows in an environment that is becoming hotter and drier. Describe how natural selection can lead to the evolution of plants that are better adapted to a hot, dry climate. Be specific about cause and effect. You may wish to review the misconception alerts.

*(Learning Outcome 4)*

# Unit II

# The Non-living World Makes Life Possible

Burton 2014

Clouds in eastern Colorado, USA.

**Matter and energy dynamics are essential to ecosystems.**

**Unit Outcomes**

- Accurately describe how energy, water, and nutrients flow through ecosystems
- Correctly apply the laws of thermodynamics to ecosystems
- Apply concepts about heat and states of matter to correctly predict climate, microclimate, vegetation, and soil properties

# Chapter 5: Sunlight, Water, and Nutrients

## Case Study Part 1: Who Caffeinated the Pacific?

https://coast.noaa.gov/states/stories/tsunami-preparedness.html

Figure 1. Coastal waters in Oregon, USA.

In 2010, researchers analyzed water samples from the Pacific Ocean all along the coast of Oregon. They found surprisingly high levels of caffeine. The levels were much higher in rural areas than they were in urban areas. There is no natural source of caffeine in the Pacific Ocean. Caffeine is found in many households in beverages, food, dietary supplements, and drugs, but how did it get into the ocean? To answer this question, researchers had to understand how water moves through ecosystems. This chapter will explore how matter cycles through the systems on Earth and how energy enters and leaves those systems.

### Learning from the Case Study

- Were caffeine levels higher near cities or in rural areas?
- Why is it surprising to find caffeine in the Pacific Ocean?

# Learning Outcomes

1. *Accurately describe and explain how water, carbon, nitrogen, and phosphorus travel through ecosystems.*
2. *Analyze how energy enters and is lost from ecosystems to make valid predictions about ecological communities.*
3. *Apply the concept of photosynthesis to make valid predictions about productivity.*

**Vocabulary Toolkit**

**Roots**
Primary = first level
Secondary = second level
Tertiary = third level

**Word Watch List**
**Producer**: Organism that performs photosynthesis, example: plant or algae
**Photosynthesis**: Process using light energy to combine carbon dioxide and water into sugar, with oxygen as a waste product
**Fixing**: Taking a molecule or element in a gas state and making it part of a solid
**Cellular respiration**: Process of breaking down sugar in to release energy. Reaction requires oxygen and produces carbon dioxide and water
**Consumers**: Organisms that get energy by eating or absorbing food. Primary consumers eat producers, secondary consumers eat primary consumers, tertiary consumers eat secondary consumers
**Decomposers**: Organisms that break down wastes or dead organisms
**Trophic levels**: Organism's energy consumption status. Producers are the first level, consumers are at higher levels depending on their food source
**Gross productivity**: Amount of photosynthesis done by producers
**Net Productivity**: Gross productivity minus the energy used by the producers, often measured in amount of tissue added by the producer

### Matter Cycles and Energy Dissipates

Recall from Chapter 1 that ecosystems include the biotic and abiotic elements of an area. Life in ecosystems depends on the input of energy and the cycling of matter. As discussed in Chapter 3, carbon, hydrogen, oxygen, nitrogen, and phosphorous are part of molecules that are essential to life. Carbohydrates and fats contain carbon, hydrogen and oxygen. Proteins contain carbon, hydrogen, oxygen, and nitrogen. DNA contains all of these elements and phosphorus.

All of these elements cycle through ecosystems in various forms. Matter and energy are conserved, but *usable* energy is lost each time it is transformed.

Water is critical to life. Recall from Chapter 3 that water can be found as a liquid, as a gas (water vapor), and as a solid (ice). All of these forms might be found in the same general location (Figure 2). The amount of water in a place, and the state the water is in, depends on climate, which will be discussed further in Chapter 6.

https://www.fisheries.noaa.gov/science-blog/alaska-salmon-travels-post-1

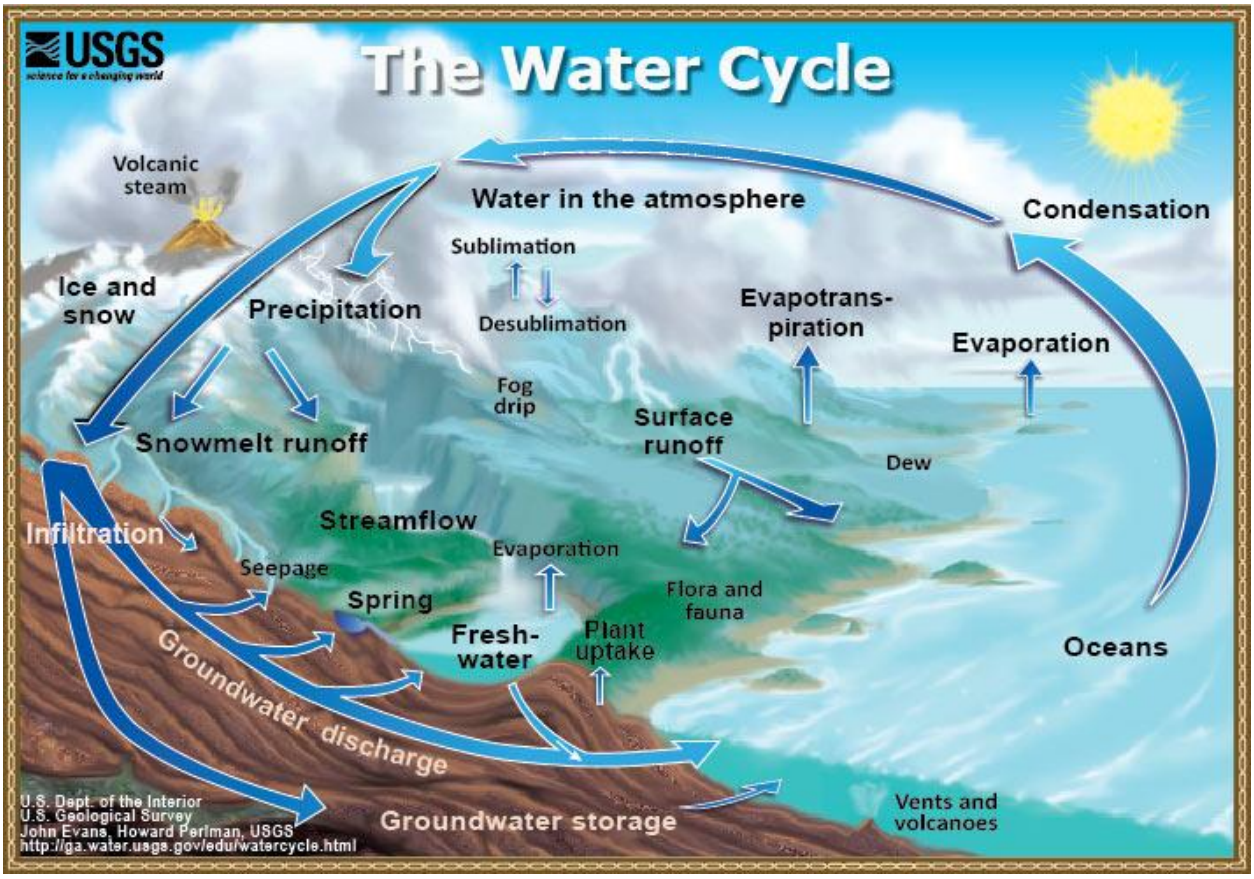
Figure 2. Water in and around a lake in Alaska, USA.

**Analyze the Figure**

- Where is water in its solid form?
- Where is it in its liquid form?
- You cannot see water in its vapor form, but what observations allow you to infer that there is water vapor in the air?

The water cycle shows matter and energy dynamics (Figure 3). Water can move through ecosystems in any of its states. Liquid water falls as rain. It flows above and below the ground. We tap into this underground water using wells. When energy is added as heat, liquid water evaporates into water vapor (experiment with this yourself; see **Do Try this At Home: Evaporation**). Water vapor moves through the air. It condenses into liquid water again, as clouds or rain. Frozen water falls as precipitation (such as snow) and moves down slopes in avalanches and glaciers. Heat can also change water from its solid state to its gas state directly. When water from snow and ice becomes vapor without becoming liquid it is called sublimation.

Water can move through organisms. We take in water when we eat or drink, and lose it in multiple ways, such as urine, feces, and sweat. We also exhale water vapor. We can “see our breath” when the water vapor in our breath becomes cold and condenses. Plants on land draw up water through their roots. Water evaporates off the plant surface, especially through the leaves (evapotranspiration). Practice using a visual model to track the movement of water in an ecosystem using **Model Skill: Flow Charts 2**.




http://water.epa.gov/scitech/climatechange/Water-Impacts-of-Climate-Change.cfm

Figure 3. The water cycle. The major ways that water changes state are evaporation, condensation, freezing, and melting. Water can also change from a solid state to a gas state in sublimation. As a liquid, water can flow above the ground or below it. When it condenses in the atmosphere, water can remain as clouds or fall as precipitation.

**Analyze the Figure**

- Name some ways that water can be stored in an ecosystem.
- What process would form dew (the water sometimes found on vegetation in the morning)?
- Where does the energy for evaporation come from?

**Do Try this At Home: Evaporation**

Put moist soil in a clear glass or plastic container. A food jar without a lid or a 2-liter bottle with the top cut off works well. Cover the top with a sheet of plastic wrap or a clear plastic bag. Make a second container that is exactly like it (as much as possible). Put both containers near a window, but cover one with a cloth to keep the light out. You can quantify the amount of evaporation by counting water droplets on the plastic wrap.

What do you predict will happen?

Where would the energy to evaporate the water come from?

Does the water have to boil for evaporation to occur?

Change a variable in your experiment, but remember to keep all of the other variables the same for both treatments. You might change the amount of surface area for evaporation by putting the same amount of wet soil in containers with different shapes. For another experiment, you might have plastic wrap on top of one container, but not the other. You could weigh the containers at the end of your experiment. The less precise your scale is, the longer you will want your experiment to run. If you live in a humid climate, you may see very little evaporation. Why is that?

**Model Skill: Flow Charts 2**

Complete the flow chart in Figure 4. Use the boxes for inputs and outputs, such as heat, water vapor, liquid water, or ice. Use arrows to show processes, such as evaporation, condensation, freezing, flow, or melting. Add boxes and arrows as needed. There are many possibilities for a correct flow chart, but your chart should allow water to complete a full cycle.

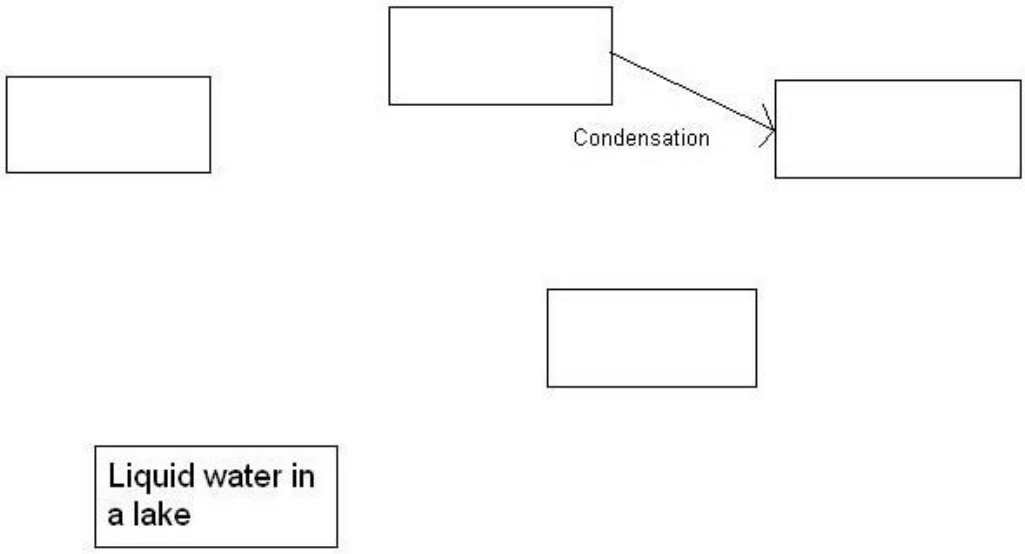
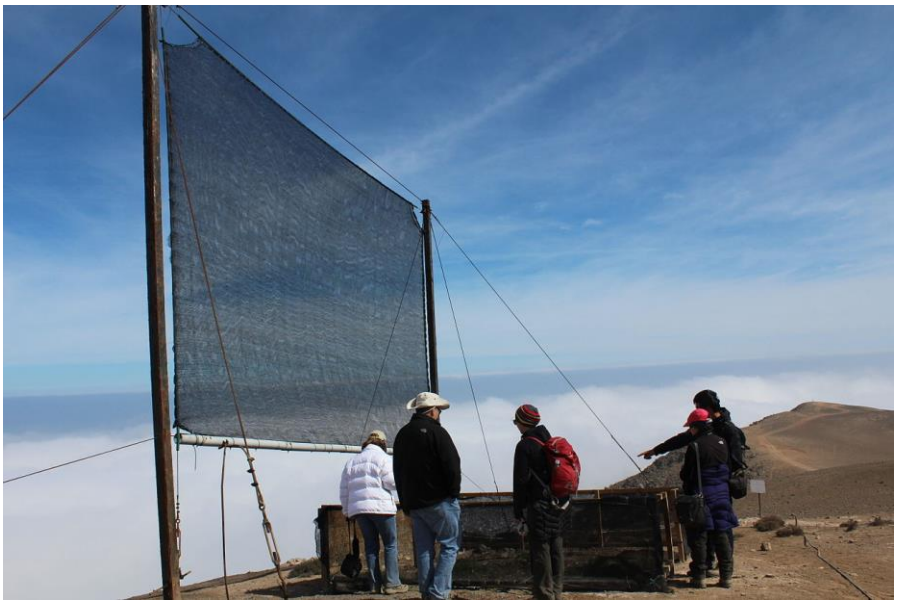



Figure 4. Incomplete flow chart of the water cycle.

All living things need water. Organisms that live in water have mechanisms to avoid taking in too much, but land species usually have to avoid water loss. People in developed nations often take water for granted, but it is a limited resource. Applying concepts of the water cycle has provided cost-efficient ways to provide safe water to people in developing nations (see **Why It Matters: Harvesting Water**).

**Why It Matters: Harvesting Water**



https://en.wikipedia.org/wiki/Fog_collection#/media/File:Atrapanieblas_en_Alto_Patache.jpg

Figure 5. A device for collecting water from fog.

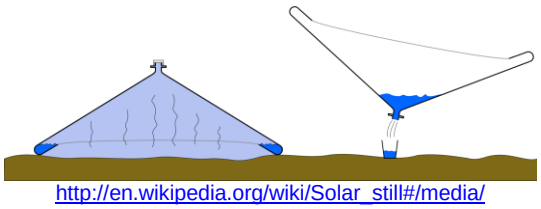
Many people have no safe, reliable supply of water. Several new or improved technologies use condensation as a way to harvest water from air. One type of device collects water from fog. Fog and clouds are basically the same thing—tiny water droplets that have condensed onto dust particles. The droplets are too small to fall as precipitation. A person who was above or below fog would call it a cloud.

Special netting is used to collect the tiny water droplets in fog (Figure 5). These droplets combine into larger droplets and finally into flowing water that can be collected for drinking and other uses. Communities that experience little rain, but have frequent fog, get the most benefits from the nets.

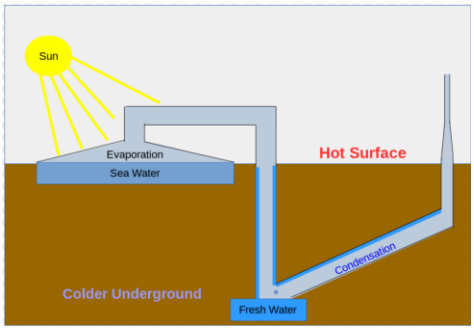
Other communities may have access to liquid water that is either salty or contaminated. Solar stills (Figure 6) use the Sun's energy to evaporate water, which then condenses and can be collected. When water evaporates, anything that was in the water (including toxins and germs) is left behind. Solar stills avoid one potential problem of the fog nets—the inclusion of dust particles in the water. Some solar stills are designed to float on water while they work. Others need to have water or moist soil added.

**Continued**

**Why It Matters: Harvesting Water, Cont.**



http://en.wikipedia.org/wiki/Solar_still#/media/File:Watercone_on_earth.svg




Engelbert Niehaus - https://en.wikipedia.org/w/index.php?curid=55237502

Figure 6. Examples of solar stills. Energy from the Sun causes water to evaporate. The water vapor then condenses on a slanted surface that allows water droplets to flow into a container, such as a trough. The source of the water can be damp soil, sea water, or even heavily contaminated water.

- Is water access a human rights issue?
- How might water access influence a society in terms of health, education, and political stability?

Evaporation cools objects because a lot of energy—in the form of heat— is needed to change water from a liquid state into a gas state. A lot of energy is also required to melt ice. In both these cases, some of the energy is transformed into the movement of water molecules and some dissipates. As that heat spreads out, it is not available to do more work.

If you took two identical containers, filled one with water, and left the other one filled with air, which would heat or cool faster? The water would stay the same temperature longer. Water is very good a holding heat. This aspect of water is important in understanding climates and microclimates, as will be discussed in Chapter 6.

**Case Study Part 2: How Did the Caffeine Get into the Ocean?**

https://www.climate.gov/news-features/climate-and/climate-coffee

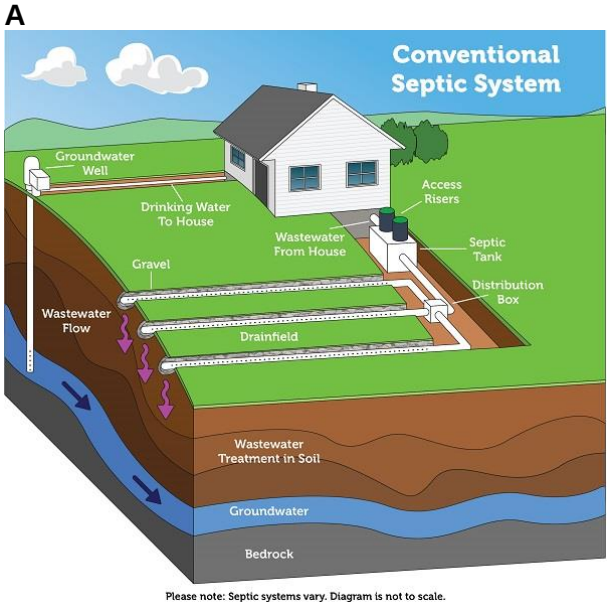
Figure 7. Caffeine in beverages, food, drugs and supplements can end up in the ocean if wastewater is not properly treated.

Some of the caffeine consumed in food, beverages, drugs, or supplements is excreted in urine. Caffeine may also end up in wastewater when people dispose of caffeinated products. How does the caffeine get from the wastewater system a home or business into the ocean? When thinking about any system, consider inputs, outputs, and processes that happen in between.

As you can see in Figure 3, all water can go to the sea eventually. The difference is how long the journey takes and what happens to the water on the way. Researchers found higher levels of caffeine in rural areas (45 nanograms/liter) than in urban areas (9 nanograms/liter). They were surprised by this at first, then they realized that while much more caffeine probably ended up in wastewater collected from cities, the urban sewage treatment systems are much more effective at removing the caffeine before it reaches the ocean.

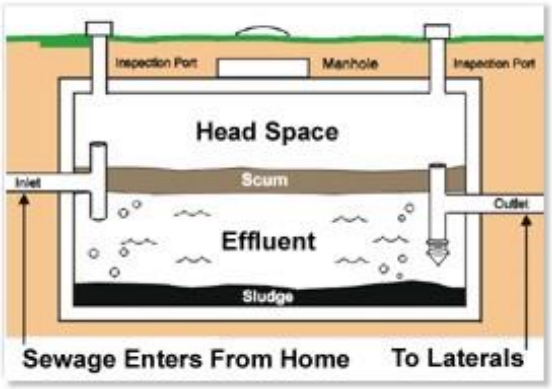
The cities along the Oregon Coast collect wastewater in sewer pipes that lead to water treatment plants. The water is filtered and treated chemically using several steps. Many contaminants are removed from the water before it is sent to the ocean. In the rural areas, buildings are usually not on a public sewer system. Instead, homes and buisnesses have their own septic systems (Figure 8). These systems are designed to trap solids and scum, while letting water filter through the soil and into the groundwater. Anything dissolved in the water might also flow into the groundwater. Groundwater can eventually reach the sea.

**A**




https://www.epa.gov/septic/types-septic-systems

**B**




http://www.nj.gov/dep/dwq/owm_home.htm

Figure 8. **A** Overview of a septic system. **B** Details of the septic tank. Waste water from the building flows into a septic tank. Solids fall to the bottom of the tank as sludge. Grease and other materials form a floating scum. The sludge and scum generally stay in the tank, while the liquid (effluent) and materials dissolved in it flow into the drainfield through the lateral pipes.

**Analyze the Figure**

- Where will the waste water go after it leaves the drainfield?
- Why might some septic systems pollute groundwater more than others?

Septic systems rely on soil, sand, and other substrate material to to filter waste water. Even if the septic system is far inland, the groundwater will probably eventually flow into a river and then into the sea. Caffeine is apparently not removed from the water by this physical filtration before the water reaches the ocean.

**Learning from the Case Study**

- Why were caffeine levels higher in rural areas than near cities?
- What other contaminants might be getting into groundwater from septic systems?
- If homes have both septic systems and wells, what problems might they have?

**Check Your Understanding**

- Describe how water moves through ecosystems.
- Explain why energy is important in the water cycle.
- Explain why Earth can last indefinitely without any new water, but it requires a constant input of energy from the Sun.

**Producers Transform Light Energy to Chemical Energy**

Plants, algae, and many microbes are called **producers** because they produce food (Figure 9). Producers combine water with carbon dioxide to make sugar and other carbohydrates in the process of **photosynthesis** (Figure 10). Taking $CO_2$—a gas—and making a solid such as sugar is called **fixing** the carbon. Recall from Chapter 4 that the sugar can then be used to make starch, cellulose, wood, and other molecules that are part of the producer.

https://www.nps.gov/olym/learn/nature/temperate-rain-forests.htm

Figure 9. Producers on land and in the water perform photosynthesis, taking in carbon dioxide and water and producing sugar and oxygen. Light energy powers the process. These producers are in the Olympic National Park, Washington.

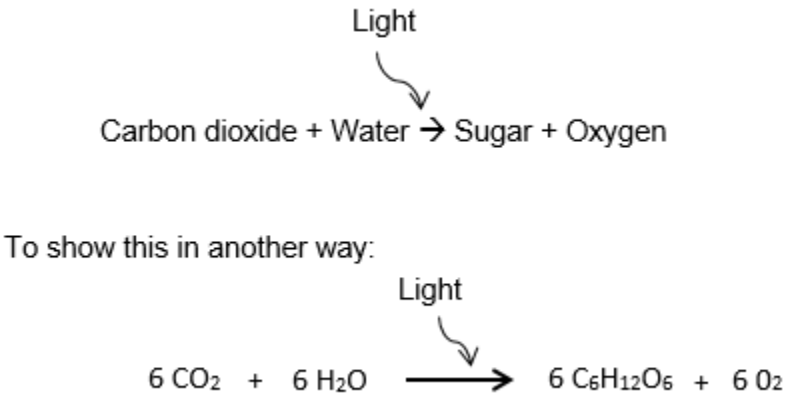



Figure 10. Two ways to show the process of photosynthesis. Both show that carbon dioxide and water are the matter inputs (or reactants) and that sugar and oxygen are the outputs (or products). Light provides the energy for the reaction. Pigments, enzymes, organelles, and other things are also critical to the process, but are not used up by the process.

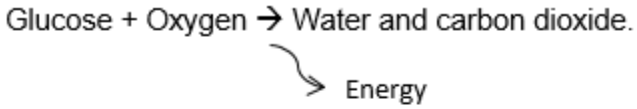
Take a closer look at Figure 10. If you count up the number of atoms of each element on each side of the arrow, you can see that they are equal. There are 6 carbons going in as $CO_2$ and there are 6 carbons in the sugar molecule. There are 12 hydrogen atoms entering as water (6 water molecules, with 2 hydrogen atoms in each) and 12 hydrogen atoms in the sugar molecule. Eighteen oxygen atoms enter (6 in water, and 2 in each of the 6 carbon dioxide molecules). There are six oxygen atoms in the sugar and another twelve leave as oxygen. This is an example of how matter is conserved—the first law of thermodynamics. The atoms are re-arranged into different molecules, but no atoms are created or destroyed. In this reaction, small molecules are taken apart and bigger ones are built from the pieces. Energy from light must be added to make this happen.

Plants on land get carbon by taking in carbon dioxide ($CO_2$) through their leaves. They absorb water and other nutrients through their roots. Aquatic producers absorb water and the dissolved carbon dioxide and nutrients over their surfaces.

**Misconception Alert: Plants take up carbon through their roots.**

**FALSE.** Plants on land can only get carbon from the atmosphere. When people look at a tree, they often have a difficult time believing that most of the mass of that tree came from a gas, carbon dioxide. If you grow plants of your own, you know that you only have to add water and a tiny amount of "plant food" to get a huge plant, or baskets full of vegetables. Some of that plant's mass comes from water, but most of the rest is from carbon dioxide.

Living things will get some (but not all) of this energy back when they break down sugar in **cellular respiration** (Figure 11). This is an example of the second law of thermodynamics: when energy is transformed, some is lost.




This can also be shown as:

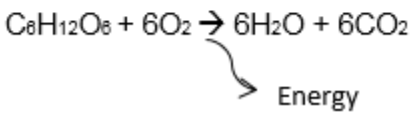
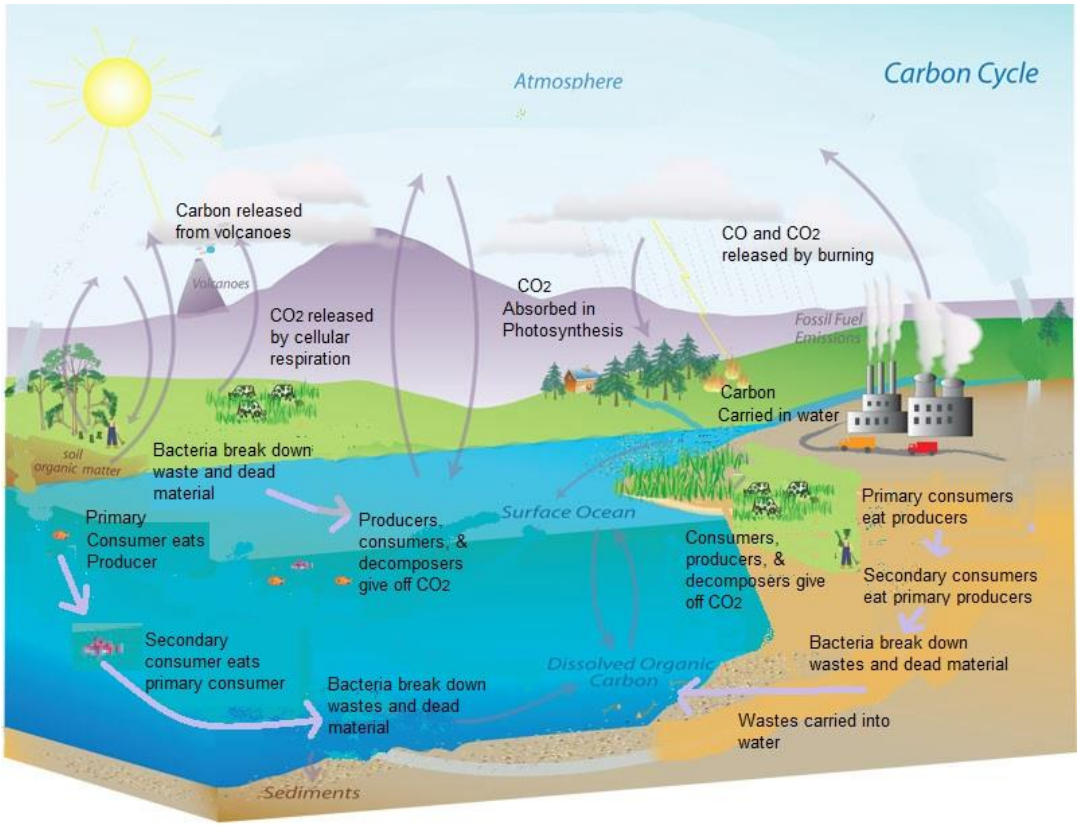



Figure 11. Two ways to show the process of cellular respiration. Both show that a sugar (glucose) and oxygen are the inputs (or reactants) and that water and carbon dioxide are the outputs (or products). The reaction releases energy that the cell can use to do work. More energy is lost as heat. Enzymes, organelles, and other things are also critical to the process, but are not used up by the process.

Most living things on Earth do cellular respiration. Even species that do photosynthesis need to break down sugar when they need energy. Look at a tree. Only the leaves do photosynthesis, but every live cell in the tree needs energy. The sugar made in the leaves travels all over the plant as sap, supplying a source of energy to cells that don't do photosynthesis. When it is dark, none of the cells can do photosynthesis. Each cell does cellular respiration to supply its energy needs. The process requires oxygen and makes carbon dioxide as a waste product.

Recall from Chapters 3 and 4 that carbon moves through the ecosystem as different molecules (Figure 12). It can be eaten as tissue of living things. It might be in fat, protein, starch, or other molecules. **Primary consumers** (herbivores) eat plants and other producers. **Secondary consumers** (carnivores) eat herbivores. **Tertiary consumers** eat carnivores. The **decomposers**—such as certain bacteria, fungi, and animals—break down dead organisms and wastes for their food. All of these organisms use cellular respiration to release the energy that producers stored using photosynthesis. Cellular respiration releases $CO_2$ into the atmosphere or water.




Adapted from: http://www.esrl.noaa.gov/gmd/outreach/carbon_toolkit/images/carbon_cycle.jpg

Figure 12. Carbon cycle. Carbon dioxide in the atmosphere enters producers, which fix it into carbohydrates. Consumers get carbon from the plants or other consumers they eat. Carbon compounds are present in wastes and dead organisms. When decomposers break down the carbohydrates, they release carbon to the atmospheric pool. Volcanoes and burning organic materials also return carbon to the atmosphere.

**Analyze the Figure**

- How does carbon get into plants?
- How does carbon dioxide leave animals?
- How do decomposers help move carbon through the ecosystem?

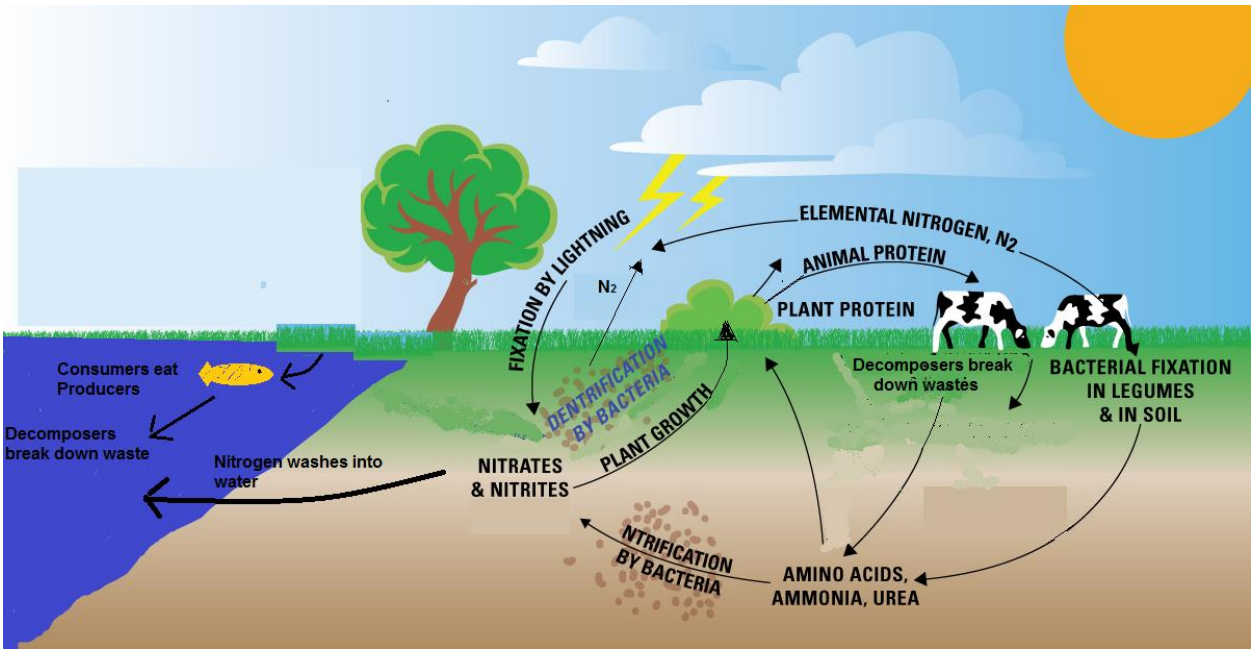
Wood, coal, oil, and similar fuels used to be part of living organisms. When they burn, the carbon that was once part of living tissues enters the atmosphere in the form of carbon dioxide, carbon monoxide and other gases. Recall from Chapter 3 that these are greenhouse gasses that can increase the amount of heat trapped in our atmosphere. Burning fossil fuels turns the molecules that once made up living things into simple molecules and releases energy. Can all of that energy be harnessed to do work? No process is completely efficient. Some energy is always lost as heat. Burning fuels is especially inefficient.

https://www.energy.gov/ne/articles/could-nations-coal-plant-sites-help-drive-clean-energy-transition

Figure 13. Emissions from a coal-fired power plant. When fossil fuels such as coal are burned, they release greenhouse gases such as carbon dioxide and carbon monoxide.

Nitrogen is a critical part of proteins, DNA, and other molecules. Decomposers return nitrogen to the ecosystem when they break down wastes and dead organisms. About 80% of the air around us is nitrogen (Figure 14). You might think that producers would have plenty of nitrogen available to them. But the nitrogen molecules in the atmosphere are made of two nitrogen atoms that are tightly bonded together. Producers cannot pull them apart. This is like dying of thirst on a raft in the ocean; the resource you need is all around you, but you cannot process it into a form you can use. Lightning has enough energy to fix nitrogen into molecules producers can use, but this is only a small amount. Some bacteria can fix the nitrogen in the atmosphere into a molecules that plants can use, such as ammonia. Some plants host nitrogen-fixing bacteria in their roots, feeding them sugar and getting usable nitrogen. Plants like this (beans and clover, for example) are called legumes.  Relationships like this between species will be discussed further in Chapter 15.

Nitrogen in ground or surface water can cause serious water quality issues. Human and other animal waste can pollute water with excess nitrogen. Humans manufacture fertilizers containing nitrogen. These fertilizers seep into groundwater, are blown to other areas by wind, or are picked up by water flowing over fertilized fields. For more information on the health risks of nitrogen in water, see **Make the Medical Connection: Nitrogen and Blue Baby Syndrome**.



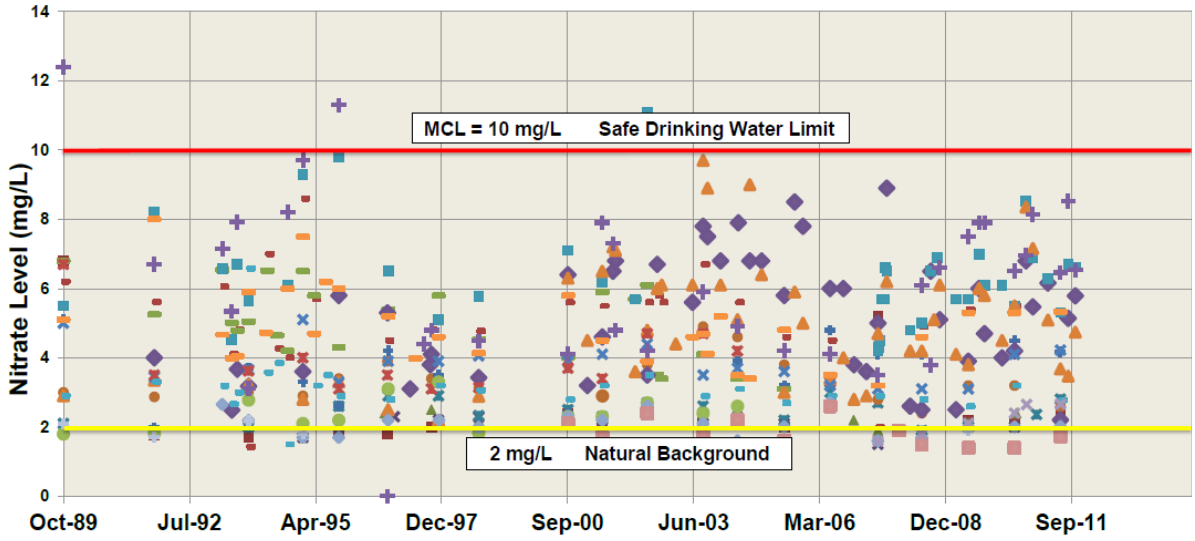

Modified from: http://toxics.usgs.gov/highlights/antibiotics_gw/

Figure 14. Nitrogen cycle. Dead organisms and wastes from living organisms add nitrogen to the soil. Plants can get nitrogen from the soil or water, but cannot draw it from the atmosphere. Certain bacteria that live in the roots of legumes can fix nitrogen from the atmosphere and fix it into forms that plants can draw in. Other bacteria turn fixed nitrogen into nitrogen in the atmosphere. Other sources of fixed nitrogen are lightning and manufactured fertilizer.

**Analyze the Figure**

- How does nitrogen get into plants?
- How does nitrogen leave animals?
- How does nitrogen get into water?

**Make the Medical Connection: Nitrogen and Blue Baby Syndrome**




Modified from: http://www.bannockcounty.us/groundwater/our-water-quality/

Figure 15. Nitrate levels in groundwater wells in Pocatello, Idaho compared to the natural level (yellow line) and Maximum contaminant level (MCL) set by the US Environmental Protection Agency (red line). Each marker is a measurement from a particular well on a particular date. The nitrate source in this area is a high concentration of septic systems.

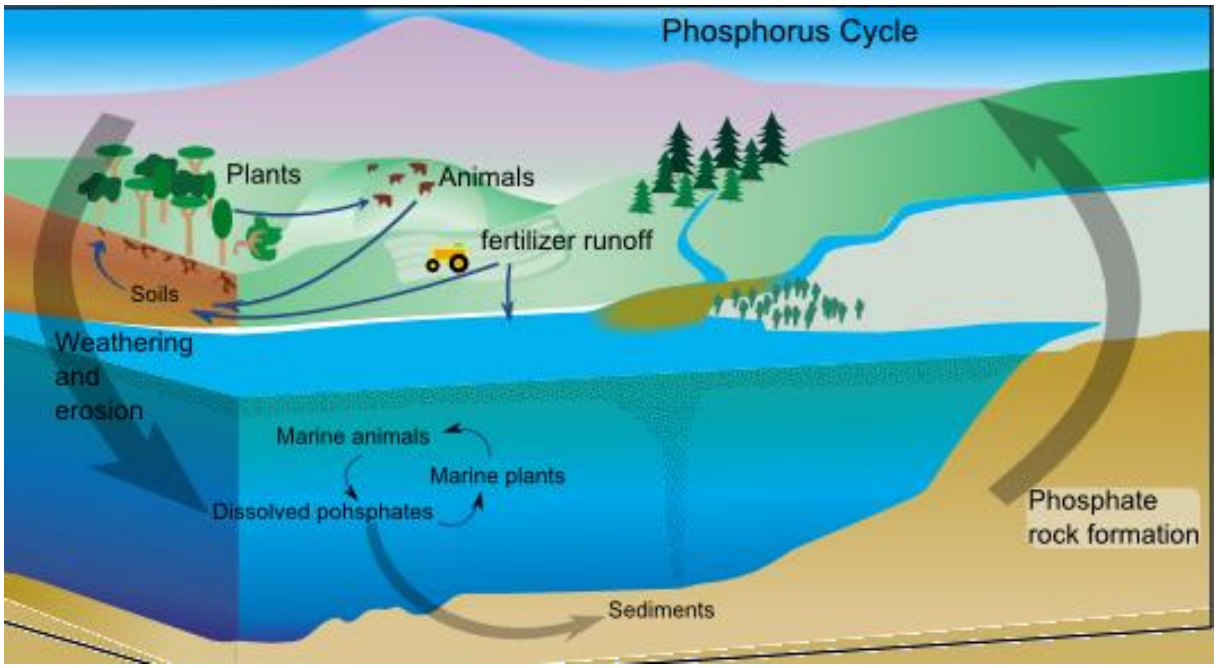
**Analyze the Figure**

- Are any of the samples above the safe drinking water level?
- What is the evidence that the nitrate level have increased due to human activity?
- Why might the readings for the same well change over time?

Nitrates are a form of nitrogen that can get into surface or groundwater from sewage or fertilizer. If too much nitrogen gets into drinking water, it increases nitrogen levels in blood and prevents the hemoglobin in red blood cells from carrying oxygen effectively. Ligher-skinned infants with this disease look blue around the mouth and other places due to a lack of oxygen. This is called blue baby syndrome, which can lead to severe illness and even death. Adults can tolerate higher nitrogen levels before they get ill.

Phosphorus is needed to make cell membranes, DNA, and other essential molecules and structures. A lot of phosphorus is trapped in rocks (Figure 16). As the rocks break down, phosphorus is released into the soil and water. Living things excrete wastes and eventually die. These wastes and dead organisms also contain phosphorus that ends up in the soil and water when they decompose (break down). Animals get phosphorus by eating other living things.

Plants draw this nutrient up through their roots. Aquatic species absorb phosphorus from water. Phosphorus is also included in manufactured fertilizers. Like nitrogen, it can pollute water.




http://commons.wikimedia.org/wiki/File%3APhosphorus_cycle.png

Figure 16. Phosphorus cycle. The major pool of phosphorus is in the soil and water. Producers draw the phosphorus in from their surrounding soil and water. Animals eat producers or other animals. Wastes and dead organisms return phosphorus to the soil and water.

**Analyze the Figure**

- How does phosphorus get into plants?
- How does phosphorus leave animals?
- How does phosphorus get into get out of rocks?

**Case Study Part 3: What Else Is In The Water?**

https://www.epa.gov/caddis/urbanization-wastewater-inputs

Figure 17. Overflows from city sewage systems are sometimes released into rivers, lakes, or the ocean without being treated.

Caffeine has been found in the water along many coasts, not just those in the Pacific Northwest of the United States. Ecologists are concerned about any effects of caffeine on wildlife and human health, but they are even more interested in water quality in general. If caffeine is entering the ocean and groundwater from kitchens and bathrooms, what else is in getting in?

Caffeine can be an important marker of water contaimination. Studies of groundwater and coastal water have shown a correlation between caffeine concentrations and concentrations of nutrients (such as nitrogen and phosphorus) and bacteria found in sewage (such as *E. coli*). These contaminants threaten human health and ecosystems. (Nutrients in aquatic ecosystems will be explored more in Chapter 9.) Increased caffeine levels in water can be an early warning that there are problems with waste management systems that drain into the area. These problems could then be fixed to avoid worse pollution from drugs, pesticides, and other toxins.

Even when urban sewage treatment plants or home septic systems are working as they were designed to, heavy rainfalls can overwhelm the systems, causing raw or partially-treated sewage to enter groundwater and the ocean. This is especially true when communities use one system for both sewage and stormwater. Comparisons of caffeine levels before and after these events could provide information on the size of the problem.

**Learning from the Case Study**

- What makes caffeine a good marker for other water quality issues?
- Would caffeine be a good marker of water quality in an area where plants (such as coffee trees or tea plants) produce caffeine?

**Check Your Understanding**

- How are carbon cycles and nitrogen cycles different?
- Which nutrients are often exchanged between the atmosphere and plants?

- Which nutrients travel in ground and surface water?

**Energy Travels through Trophic Levels**

As you know from the second law of thermodynamics, every time energy is converted from one form to another, some is lost as heat. Organisms that get their energy directly from the Sun have the most energy available to them. **Trophic levels** refer to the way organisms get their energy (Figure 18). As discussed earlier, producers do photosynthesis, producing food using energy, water, and $CO_2$. Primary consumers eat plants and other producers, secondary consumers eat herbivores, and tertiary consumers eat carnivores. The decomposers break down wastes and dead organisms. They are not included in the pyramid, but are critical because they keep energy and nutrients circulating through an ecosystem.

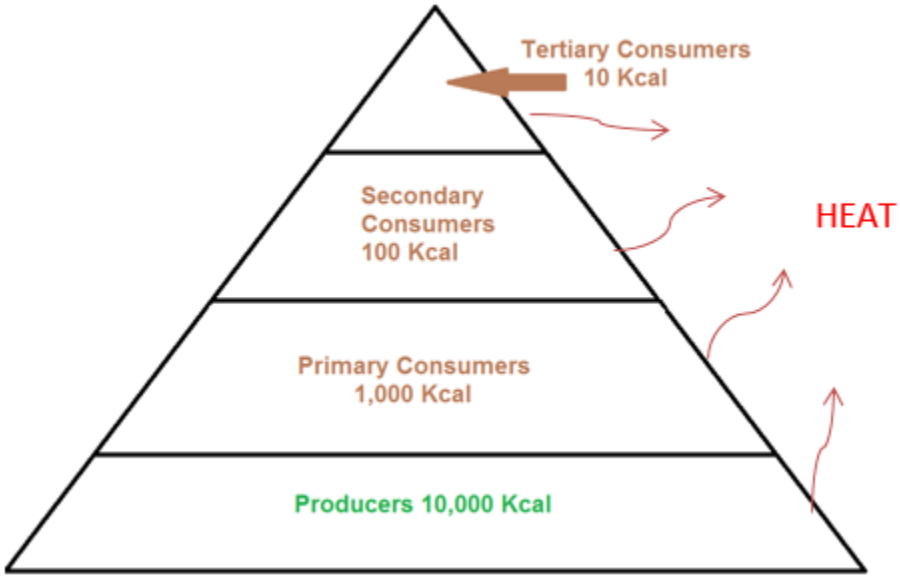



Figure 18. Energy available in trophic levels. Kcals are units of energy.

**Analyze the Figure**

- How much energy is usually lost between trophic levels
- Why is the shape a pyramid?
- Why are there so few large carnivores?

One way to measure energy is number of calories. The word “calorie” that you see on food packaging is actually a kilocalorie (1,000 calories), abbreviated as “kcal.” In Figure 18, you can see the number of kilocalories present in the trophic levels in a hypothetical community. Generally speaking, only about 10% of the energy in one trophic level is available to the next trophic level. The rest is used for metabolic needs of organisms or lost as heat.

You would see a similar pattern in mass. The producers would weigh at least ten times more than all of the primary consumers. The primary consumers would weigh much more than all of the secondary consumers eating the primary consumers. The total mass of any level of the food chain is much smaller than the mass of the level below it. Less energy is available for the work of building and powering the organisms on the higher level. A consumer must eat many times its body weight over its lifetime to get enough energy for its needs. Energy is constantly being used to do work and lost as heat. One result of a consumer eating many other individual organisms is that it may accumulate toxins, as described in **Why It Matters: The Controversy over DDT**.

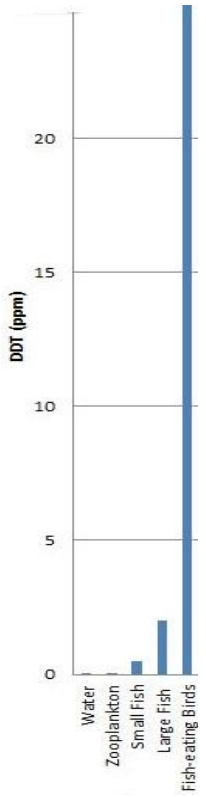
**Do Try this at Home: Trophic Levels and Numbers**

Go to a local area where you can see plants and animals. If that isn't possible, look at a picture or video of a natural area. Look at all of the green things. About how much of what you see is green? Roughly estimate the percentage. What percentage of the living things would be herbivores or primary consumers? These might be insects, which can be difficult to see, but make an estimate. How many carnivores do you see? These might include spiders or birds that eat insects. Consider why some things are more common than others.

**Why It Matters: The Controversy over DDT**

DDT was used in World War II, then in civilian areas to kill disease-carrying mosquitoes and other insects. In 1962, biologist Rachel Carson's book, *Silent Spring* warned that DDT and other pesticides were dangerous to birds and other animals, including humans. DDT was banned in the United States in 1972. International agreements also restrict the use of DDT.

Low levels of toxic materials in the environment can be dangerous for animals at higher trophic levels. At every level, animals have to eat a lot of whatever is in the level below them. Tiny animals called zooplankton are often eaten by fish (Figure 19). If the water that zooplankton live in contains toxins, some of those toxins will end up in their tissues. The small fish eat that eat zooplankton add toxins to their own tissues as they eat.




**DDT in Fish-eating Birds**
**25 ppm**

**DDT in Large Fish**
**2 ppm**

**DDT in Small Fish**
**0.5 ppm**

**DDT in Zooplankton**
**0.04 ppm**
**4 X $10^{-2}$**

**DDT in Water**
**0.000003 ppm**
**3 X $10^{-6}$**

Figure 19. Example of how DDT in water can become concentrated in the tissues of animals at higher trophic levels. Ppm means parts per million.

Some people argue that diseases carried by insects are worse than the effects of DDT and want more use of insecticides, especially in countries where mosquitoes carry malaria.

- Should DDT be used in countries where people are dying of malaria?
- What scientific, legal, economic, cultural, and ethical issues are involved in making a wise decision about regulating DDT?

Where does all of the energy go? Consider a paycheck as an analogy. Your gross income is based on your salary or your hourly pay and hours worked. Of course, you do not actually receive all of this money in your paycheck (Figure 20). Deductions are taken for taxes and various other things. Your actual paycheck is your net income. After you have spent money on various necessities, you may have a fraction left over for savings.

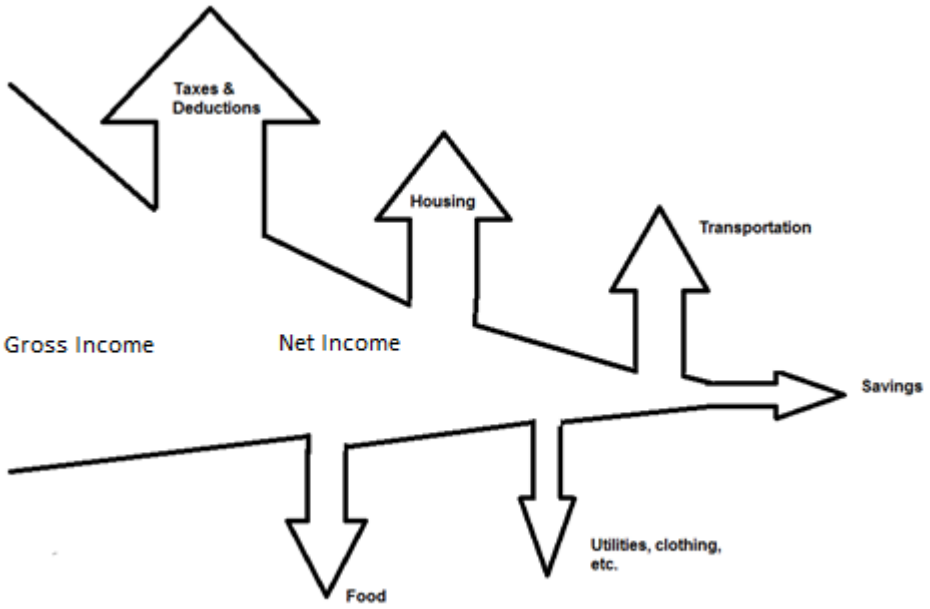



Figure 20. Flow chart demonstrating the possible flow of money from paycheck to savings.

In an ecosystem, energy enters as light. Some of that light reaches plants and other producers and can power photosynthesis. Some of it is reflected or lost as heat (Figure 21). **Gross productivity** is the total amount of photosynthesis. Producers will use some of that energy to meet their own needs. The amount of energy left for producers to invest in their own tissues is the **net productivity**, which can be measured as growth (plant biomass, number of algae, or other measures). For more on this topic, see **Taking It Further: Measuring Productivity**. When an herbivore eats all or part of the producer, it gets a part of the energy that was in the producer tissue, but it spent energy finding and digesting the plant tissue. It also spends energy on its own life support, movement, protection, and other functions. This leaves a fraction of the original energy for making biomass that will go to the carnivore that eats the herbivores. Only a tiny portion of the energy that entered the ecosystem is available for making carnivore biomass. In later chapters, you will be able to apply your understanding of how nutrients and energy flow through ecosystems to explain and predict many ecological patterns.

Any process—including photosynthesis—is limited by the availability of inputs. If any of the inputs is not available, the process stops. Productivity could be limited by water, light, or carbon dioxide. Nutrients such as nitrogen or phosphorus can also be limiting because they are needed for the chemicals and structures that make the process of photosynthesis happen. Productivity

on land is often limited by water. Productivity in water is often limited by light or nutrients. Having more of one input will not make up for the loss of another input. For example, if water is limited, having a lot of light will not allow photosynthesis to continue. For more on this topic, see **Testing Hypotheses: Does Precipitation Limit Productivity?**

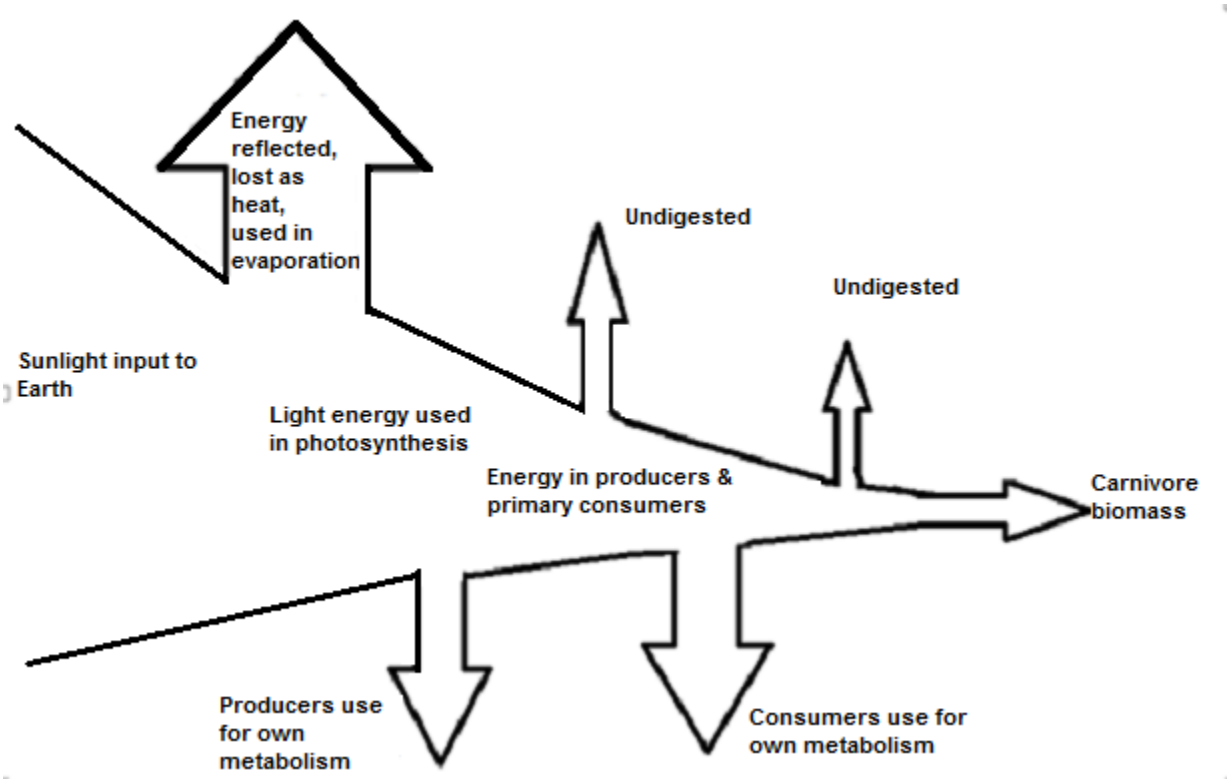



Figure 21. The flow of energy in an ecosystem. Only a small fraction of incoming energy makes it to the next trophic level.

**Taking It Further: Measuring Productivity**

Primary productivity is the total amount of photosynthesis done by producers. This may seem fairly easy to measure. You can measure how much mass increased in a certain time period. Will this be gross productivity or net productivity?

If you wanted to measure net primary productivity on a prairie, what would you do? You might mow a specific area and weigh the plant material you collected, then come back later, mow a patch the same size, and see how much more it weighed. But what about the roots? Digging up roots that go two meters down and spread out to very tiny, delicate ends would be very difficult. Often, researchers avoid this problem by talking about above-ground productivity. How would you measure above-ground productivity with trees?

In aquatic systems, the producers are usually algae. These move freely in the water instead of staying put like grasses. They may also have very short lifespans, so it is difficult to measure what is new growth just by collecting them. Researcher may have to use methods like introducing carbon isotopes to an area. As producers fix the carbon during photosynthesis, their tissues become slightly radioactive, and this can be measured.

**Testing Hypotheses: Does Precipitation Limit Productivity?**

In terrestrial systems, water and sunlight tend to limit productivity, but other factors, such as nutrients may be important as well. One way to test whether a variable is limiting is to see what happens when the amount of that variable is high or low. In natural systems, light input and nutrients have little year-to-year availability, but precipitation can vary a lot. This allows researchers to see whether increases in precipitation lead to increases in productivity.

Nippert et al. (2006) studied above-ground productivity on Konza Prairie. The grasses on this prairie are adapted to hot, dry conditions (Chapter 8 will discuss these C4 plants). Other plants on the prairie, called forbs, are not. Forbs are herbaceous plants, meaning that they are not grasses and are not woody, like shrubs and trees.

Hypothesis: Precipitation limits above-ground productivity in grasslands.

Konza Prairie is a Long-Term Ecological Research site, so climate data are available for many years. Researchers collected samples of above-ground plant growth, separated the plants by type, dried, and weighed them. They then used the samples to estimate the total net productivity (Figure 22).

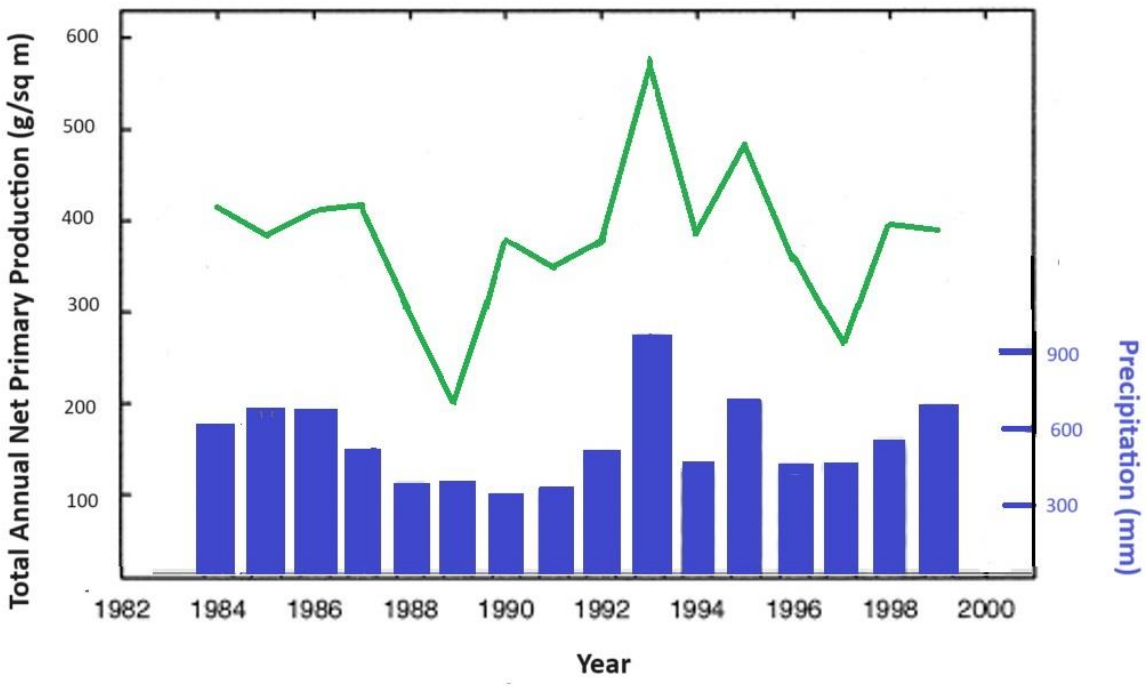



Figure 22. Total annual net primary productivity for grasses and forbs compared to annual total precipitation on Konza Prairie. Note the break in the left Y-axis.
Modified from: Nippert, J. B., Knapp, A. K., & Briggs, J. M. (2006). Intra-annual rainfall variability and grassland productivity: can the past predict the future?. *Plant Ecology*, *184*(1), 65-74.

**Analyze the Figure**

- Do years with the lowest precipitation tend to be years with the lowest total productivity?
- Do years with the highest precipitation tend to be years with the highest total productivity?
- Does productivity tend to be higher in years after high precipitation?

**Evaluate the Hypothesis**

- Is the hypothesis supported or refuted by the data?
- Could other factors still limit productivity in the grassland?

**Case Study Part 4: Where Does the Caffeine Go?**

https://www.fws.gov/carp/media/oregon-or-western-floater-mussel

Figure 23. Mussels (*Mytilus* sp.) live along the Oregon Coast in the zone between high and low tides.

If caffeine is in the water, does that mean it is dangerous to the organisms that live there? Researchers tested whether mussels were affected by caffeine at a dose of 50 nanograms/liter (Figure 24). This was in the range of caffeine levels found in waters near the Oregon Coast. The mussels produced a protein that they make in response to environmental stress.

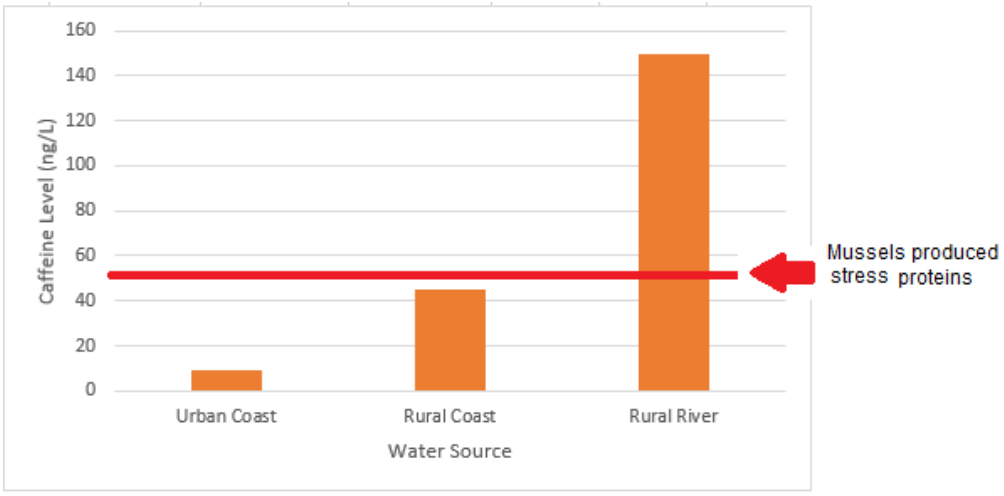



Figure 24. Maximum levels of caffeine in the water found near the Oregon coast (bars) and level known to cause stress hormone production by mussels (red line). Based on data from: Granek, E. (2012). Caffeine as a Contaminant of Freshwater and Marine Systems. *Journal of Caffeine Research. September*, *2*(3), 105-108.

**Analyze the Figure**

- Does this graph tell you whether mussels would produce stress hormones at a caffeine level less than 50 ng/L? Explain your answer.
- Which of the three location types (urban coast, rural coast, or rural river) probably have caffeine levels that influence the health of mussels? Explain your reasoning.

Other studies have shown that caffeine may reduce the reproductive ability of the mussels and the function of cells in their immune sytem. Organisms have limited amounts of energy, nutrients, and other resources to spend on various activities. If they are dealing with a challenge such as the caffeine in the water, they may have fewer resources to spend on reproduction. For more discussion of managing limited resources, see **Evolutionary Perspective: Allocating Resources in a Changing Environment**.

Caffeine does not stay in the tissues of animals that consume it, so its levels would not necessarily be higher in animals at higher trophic levels. This may not be true for other toxins that are entering with the wastewater. The caffeine is diluted as it spreads out in the ocean and breaks down after about a month. Other toxins in the wastewater may last longer.

**Learning from the Case Study**

- What is the evidence that levels of caffeine might be high enough to influence the health of mussels?
- Why wouldn't we expect higher levels of caffeine in higher trophic levels?

**Evolutionary Perspective: Allocating Resources in a Changing Environment**

https://commons.wikimedia.org/wiki/File:Zebra_mbuna_(Maylandia_zebra)_mouthbrooding.jpg

Figure 25. Many cichlids carry their eggs and young in their mouths.

Energy, nutrients, water, and other resources can all be limited. An organism's physiology allocates (distributes) these resources to different processes. For example, if an animal is spending a lot of energy protecting itself from predators, it will probably have less to invest in its immune response and be vulnerable to diseases and parasites. If a plant allocates more resources to reproductive output, it may have less to invest in growth.

Time is another important limited resource. For example, fish from the family Cichlidae hold offspring in their mouths to protect them from predators. They cannot eat while they are doing this, so there is a trade-off between eating and caring for offspring. Sometimes an animal can do two things at once, such as chewing while watching for danger.

We would expect organisms to be shaped by natural selection so that they allocate their limited resources in a way that would increase their fitness. However, the environment changes. If an organism always allocated its time, energy, and nutrients the same way, it would be at a disadvantage compared to another individual in the population that could adjust its allocation. An individual that always reproduced a certain amount would do worse in both very good and very poor conditions than an individual that put its energy into survival when resources were limited and put extra energy into reproduction when resources were available. The ability to be flexible may come at a cost too. Organisms may have to invest their scarce resources to make structures or chemicals just in case they are needed.

So natural selection may favor a range of potential allocation "strategies" that depend on the environment. These are not the result of organisms "doing the math" to figure out how to spend their resources. They are the result of physiological or behavioral patterns triggered by resource levels or other environmental cues. Organisms that live in very stable environments may be under less selection pressure to be less flexible in their allocation strategies.

**Check Your Understanding**

- Why does life on Earth require a constant input of energy?
- What inputs are required for photosynthesis? What happens when one of these is limited?
- Why is there less biomass and energy at higher trophic levels?

# Key Concepts

- The major elements in living things are carbon, hydrogen, oxygen, nitrogen, and phosphorus, which are found in molecules critical to life.
- Matter may enter organisms as they eat, drink, take in gasses, or absorb nutrients. It may leave as they eliminate wastes, expel gasses, lose parts, or decompose after death.
- Producers use the energy of the Sun to fix carbon dioxide and water into sugar during photosynthesis. Most organisms, including producers, harvest some of this energy in cellular respiration.
- Usable energy is lost as it is transformed in ecosystems.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately describe and explain how water, carbon, nitrogen, and phosphorus travel through ecosystems.*
2. *Analyze how energy enters and is lost from ecosystems to make valid predictions about ecological communities.*
3. *Apply the concept of photosynthesis to make valid predictions about productivity.*

1. A classroom sets up an aquarium with mud, water, algae, and small shrimp-like animals that eat algae. They cover it with a sheet of clear plastic.
   A. Will the students have to add food to the aquarium? Explain your answer. *(Learning Outcome 1)*
   B. Will the aquarium need to be in the Sun in order to keep the animals alive? Explain your answer. *(Learning outcomes 2 and 3)*
   C. The students wonder why beads of water form on the inside of the plastic sheet. Explain what is happening. *(Learning outcome 1)*
   D. Will there be a greater *total* weight of algae or animals? Why? *(Learning Outcomes 2 and 3)*

E. Assume that the aquarium is sealed. Will its weight change over time? Explain your answer. *(Learning Outcome 1)*

2. Imagine that you started with 10 kg of dry soil in a container, planted a tiny seed, and added water over a few years until a large plant grew. You went out of town for a month, and when you came back, the soil and plant were completely dry. The dried out plant now weighs 5 kg.

   A. The plant is mostly made of cellulose, starch and sugars. Where did the plant get the elements to make these biomolecules? Your answer will not be the same for all of them. *(Learning Outcome 1)*
   B. About how much would the dry soil weigh? Explain your answer. *(Learning Outcomes 1 & 3)*

3. What do you predict would happen if an ecosystem had no decomposers? Support your prediction with evidence and reasoning. *(Learning Outcome 1)*

4. Refer to Figure 26.

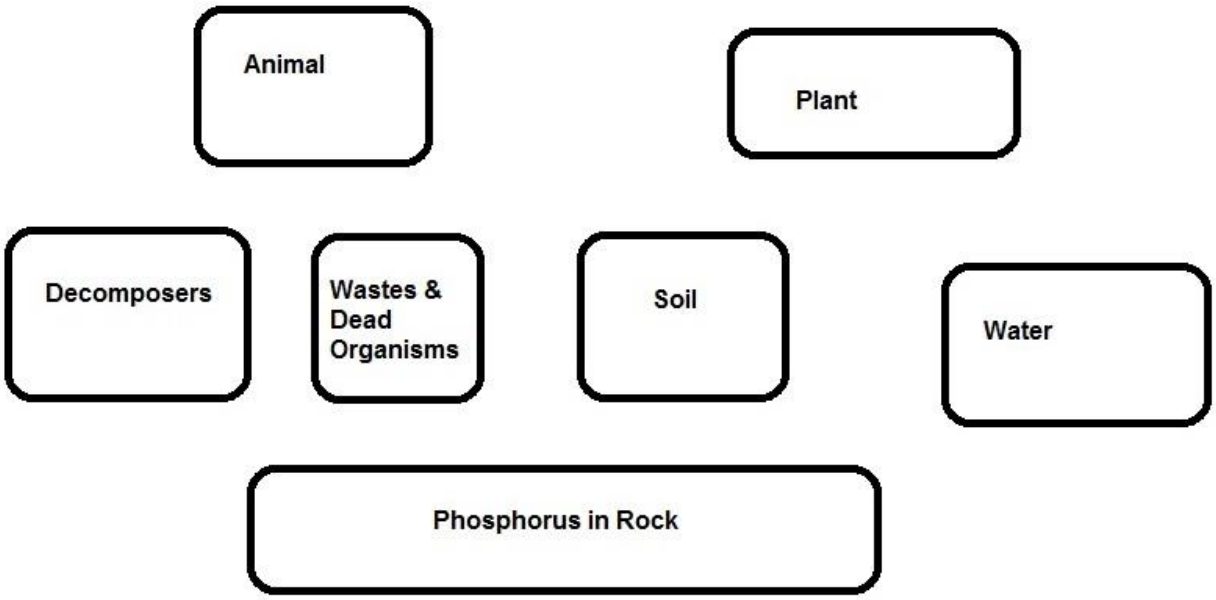



Figure 26. Incomplete phosphorus flow chart.

   A. Complete the flow chart to show how phosphorus might travel from one organism to another. Use arrows to describe the process that moves it. *(Learning Outcome 1)*
   B. How would your chart be different if you were showing the nitrogen cycle? *(Learning Outcome 1)*

5. Refer to Table 1.

   Table 1. Information on the availability of water and sunlight for three different cities. Think of the temperature as an indirect measure of light.

| **Location** | **Annual Rainfall (mm)** | **Average Temperature (ºC)** |
|---|---|---|
| Tucson, AZ | 216.9 | 21.1 |
| Olympia, WA | 1253.2 | 9.8 |
| Acunsion, Paraguay | 1366 | 23.2 |

A. Where would you expect to find the highest plant productivity? Explain how your observations in the data led to your prediction. *(Learning Outcome 3)*
B. Where would you expect to find the highest total mass of primary consumers? Explain how your observations in the data led to your prediction. *(Learning Outcomes 2 & 3)*

**Unit II: The Non-living World Makes Life Possible**

# Chapter 6: Weather and Climates

## Case Study Part 1: Killer Tornado

https://vlab.noaa.gov/web/nws-heritage/-/tragedy-at-joplin-the-ef-5-of-may-22-2011

Figure 1. Joplin, Missouri, USA was devastated by a powerful tornado in 2011.

When the tornado warnings sounded in Joplin, Missouri on May 22, 2011, many people did not bother to take shelter. Joplin had been struck by two other tornadoes since 1971 and tornado warnings were fairly common. Residents didn't know that they were in the path of one of the most deadly and destructive tornadoes to hit the United States in recent history and that they had only 20 minutes to prepare. The tornado gained power as it ripped through the area, destroying concrete buildings and throwing thousands of large vehicles through the air. The mile-wide tornado reduced large parts of the community to foundations and debris. In little more than 30 minutes, it killed almost 160 people and caused almost 3 billion dollars' worth of damage.

Tornadoes can strike almost anywhere in the continental United States, but are most common from Texas to South Dakota and in the neighboring states. They can happen any day of the year, but they are most common from late spring to early fall. What causes these storms and why do they happen where and when they do? This chapter will explore how factors such as latitude, elevation, and bodies of water influence weather and climate at different scales.

**Learning from the Case Study**

- Are tornadoes equally likely at all times and places?
- What are some other forms of severe weather?

# Learning Outcomes

1. *Accurately describe and explain the influence of latitude and altitude on temperature*
2. *Explain how heat movement and storage influence weather and climate*
3. *Analyze how temperature and geography influence precipitation*
4. *Provide valid predictions for how aspect, color, shading, & evaporation will influence microclimate*

**Vocabulary Toolkit**

**Word Watch List**

**Climate**: Long-term view of weather
**Equator:** Imaginary line that splits Earth into equal northern and southern halves
**Latitude**: Imaginary lines that measure distance from the equator
**Humidity**: Amount of water vapor in air
**Relative humidity**: Amount of water vapor in air compared to the maximum potential level of water vapor. As temperature increases, the maximum increases
**Dewpoint**: Temperature at which water vapor will condense into liquid water
**Rain shadow**: Drier climates created when precipitation falls on other side of mountains
**Lake effect**: Increased precipitation—usually snow—caused by air masses picking up moisture from lakes
**Microclimate**: Small scale climate differences
**Nurse plants**: Plants that create favorable microclimates for other plants
**Substrate**: Any surface, such as grass, sand or concrete
**Aspect**: Direction a slope faces

## Latitude Influences Climate

**"Climate is what we expect, weather is what we get."—Mark Twain**

If you go outside right now, you can experience weather. You might notice the temperature, the wind, whether it's sunny or cloudy, whether it's raining or snowing, and whether the air feels dry or humid. If you look at the records for the weather over a long period of time, you would learn about your area's **climate**. You can't predict exactly what the weather will be like a year from today, but you probably have a good idea about what the weather tends to be like in your area. Your area's climate is mostly a result of the geography of where you live, though it will vary due to several variables. The climate in your area is one of the major factors determining your soil and water conditions and what species can live in your area.

As noted in Chapter 3, light and heat are forms of kinetic energy. When the sun's rays hit an object, light can be absorbed, reflected, or even go through transparent materials such as water or glass. Light energy absorbed by an object can be given off as heat (Figure 2). Water is particularly good at storing heat. Heat moves from warmer to colder things and can be transferred by objects that are in direct contact, or from one part of an object to another. Air, water, and other fluids can move heat from one place to another.

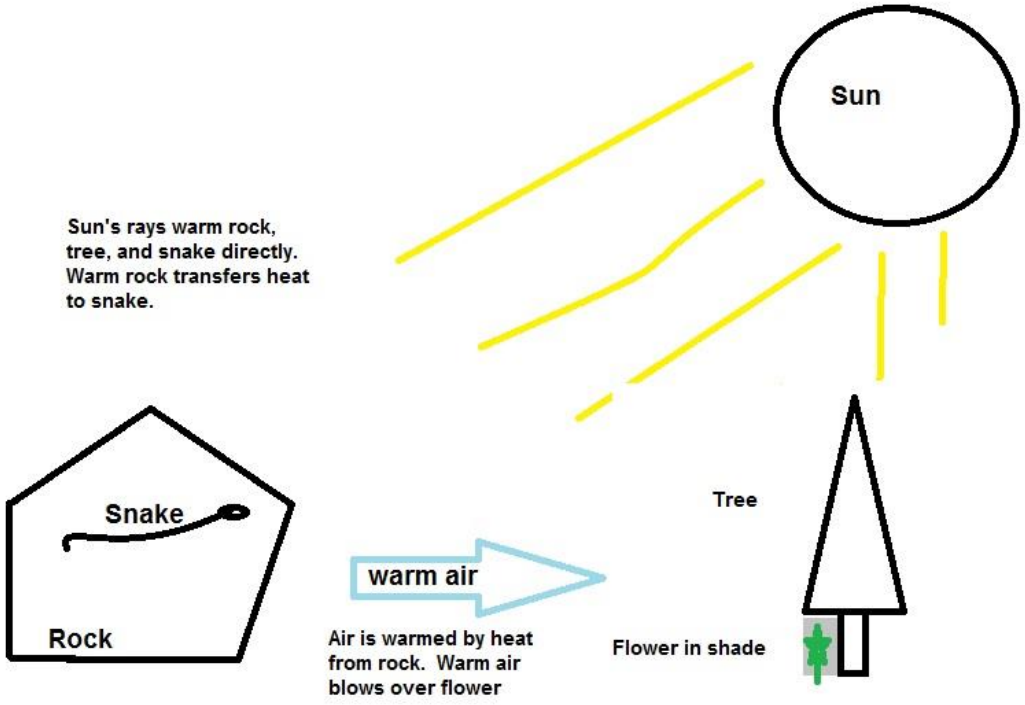
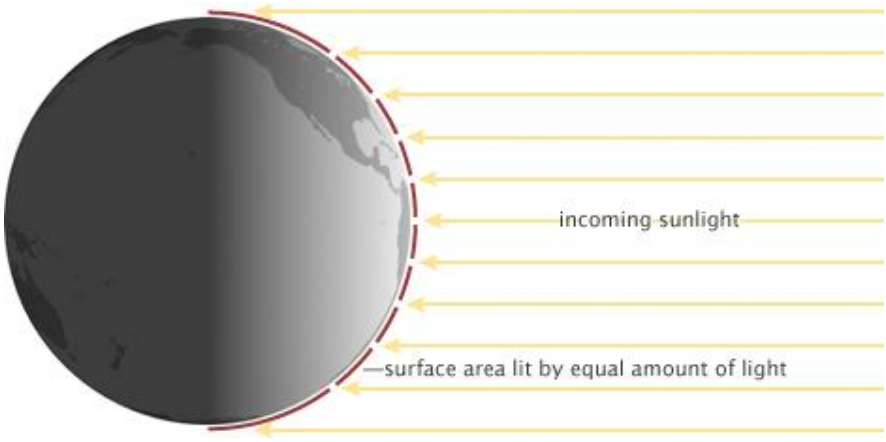



Figure 2. Examples of heat movement. The sun's rays can heat an object directly or the heat can be transferred by contact or movement of air or water.

**Analyze the Figure**

- The flower is in the shade. What are some ways it receives heat?
- Why might the snake avoid the rock in the early morning?
- If the air and rock are the same temperature, why would the snake warm up faster on the rock than on the ground?

Location on Earth determines the amount of sunlight a place receives. Places near the **equator**—the imaginary line halfway between the North Pole and South Pole—get fairly direct sunlight all year long. Distance north or south of the equator is measured as **latitude**. The equator is at zero latitude and numbers increase to the north and south. Places near the poles get sunlight at more of an angle, due to their position with respect to the sun. As the surface of Earth curves away from the equator, the amount of solar radiation reaching Earth per unit area decreases because of the curve (Figure 3).




http://earthobservatory.nasa.gov/Features/EnergyBalance/page2.php

Figure 3. At the equator sunlight hits Earth more directly than it does near the poles. The curved red lines show the area that incoming light is spread over.

**Analyze the Figure**

- Which red lines are the longest?
- Which areas get the least amount of light per unit area?
- How would you describe the general pattern shown in the figure?

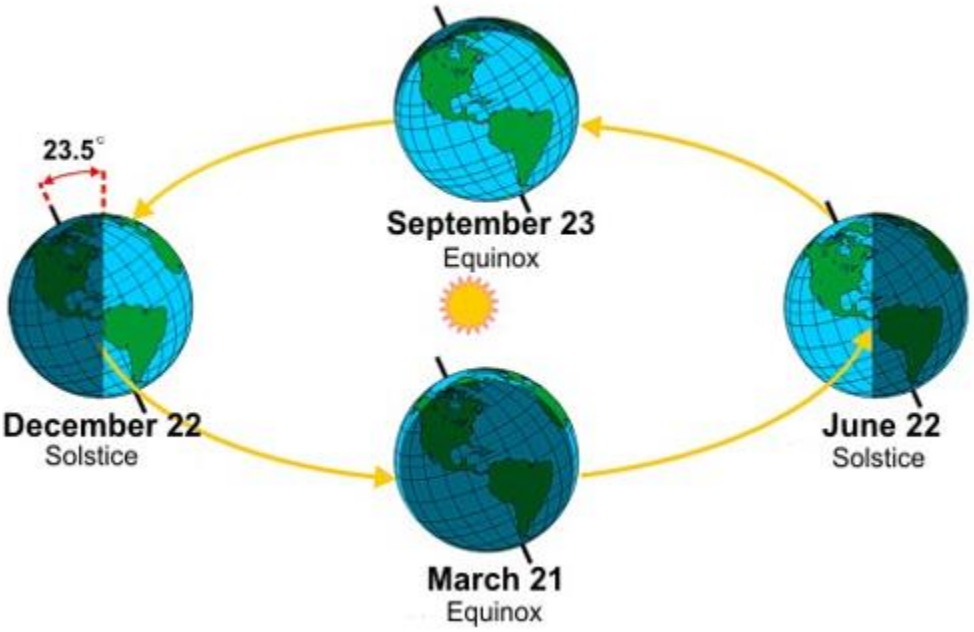
**Do Try this at Home: Light and Angles**

Hold a flashlight in one hand and a spherical object (basketball, cantaloupe, etc.) in the other hand. Imagine the equator on your sphere or mark one with tape or a pen. Shine the flashlight directly at the "equator." Notice how bright the light is where it hits the sphere. Now move the flashlight directly up just a bit. Do not move it closer to, or farther from the sphere. Notice how the light "smears" across the surface of the sphere? Relate this to why it's colder near the poles than near the equator. Think about why the sun feels hotter when it is directly overhead.

You can use weather sources to find the temperature at different times of day. As you look at larger datasets (weeks, months, or years), you will probably see clear patterns showing the time of day that is usually warmest. What pattern do you predict? Explain your prediction.

Earth has a tilt of about 23.5 degrees (it "wobbles" a bit). This is means that as Earth makes its annual orbit of the Sun, the Sun's rays hit the Northern and Southern Hemispheres unequally most of the year (Figure 3). In the summer, the Sun's rays hit an area more directly and the Sun is visible for more than half of the day. The increased solar input leads to higher temperatures. In the winter, the rays hit at more of an angle and the day length is less than 12 hours. The solar input is lower, resulting in lower temperatures. Near the equator, there is very little variation in daylength and total solar input throughout the year. Near the poles, the variation in solar input is extreme. The poles have distinct seasons, but the polar summers are still very cold. Nights and days at the poles can last for months. Extremes in daylength can influence human health (see **Make the Medical Connection: Seasonal Affective Disorder**).

The Northern and Southern Hemispheres have opposite seasons (Figure 4). At the equinoxes (March 21$^{st}$ and September 23$^{rd}$), the day and night are each 12 hours long in both hemispheres. When more of the Northern Hemisphere is tilted toward the Sun, less of the Southern Hemisphere is tilted toward the Sun. The solstices are either the longest day of the year (summer solstice) or the shortest (winter solstice). The summer solstice in the Northern Hemisphere (June 22$^{nd}$) is the winter solstice in the Southern Hemisphere. The winter solstice in the Northern Hemisphere (December 22$^{nd}$) is the summer solstice in the Southern Hemisphere.




Modified from: http://www.srh.noaa.gov/jetstream/global/global_intro.htm

Figure 4. The tilt of Earth in relation to the Sun creates seasons (the scale is extremely distorted in order to show how the light is hitting Earth's surface). Note that the axis is pointed in the same direction as Earth orbits the Sun.

**Analyze the Figure**

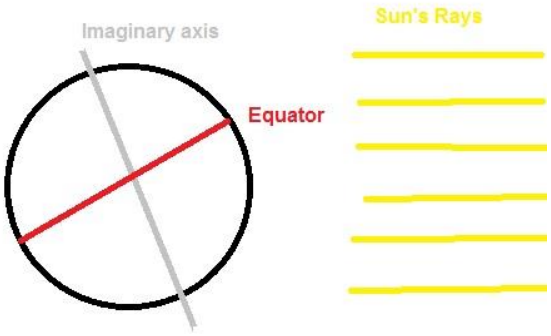
- If you were in space between Earth and the Sun on June 22, would you see more of the Northern Hemisphere or the Southern Hemisphere?
- On December 22, would you see more of the Northern Hemisphere or the Southern Hemisphere?
- When would you see both hemispheres equally?

**Misconception Alert: It's colder in winter because we are farther from the sun.**

**FALSE.** It is colder in winter because the sun's rays are hitting Earth at a greater angle. The sunlight is less intense at a greater angle than it is when the rays hit more directly. This is also why it is colder closer to the poles.

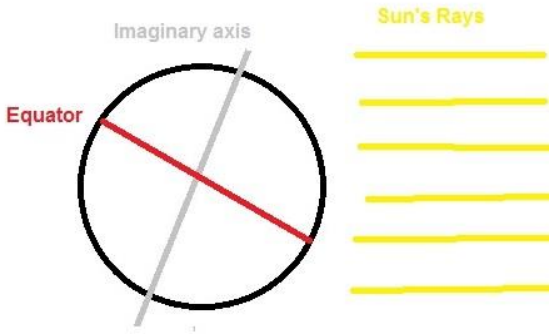
The amount of light reaching each hemisphere can be shown as a schematic (Figure 5). As light hits Earth's surface at a greater angle, less energy is delivered to a location.

**A**



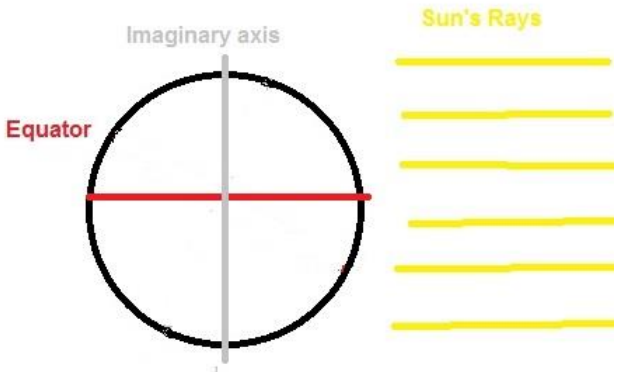

Solstice—December 21-22
Winter in the Northern Hemisphere
Summer in the Southern Hemisphere

**B**




Solstice—June 21-22
Summer in the Northern Hemisphere
Winter in the Southern Hemisphere

**C**




Equinoxes
March 20-21 and September 22-23

Figure 5. Difference in the angle of the Sun's rays during different seasons. In the middle of June, the Northern Hemisphere receives much more of the Sun's energy than it does in the middle of December. This pattern is reversed in the Southern Hemisphere. At the equinoxes, the Northern and Southern Hemispheres get an equal amount of light.

**Analyze the Figure**

- Assume that the yellow lines are a measure of the amount of light hitting an area. During the December solstice, which hemisphere receives more light?
- How does this figure relate to Figure 4?

**Make the Medical Connection: Seasonal Affective Disorder**

People at high latitudes in either hemisphere have short days in winter. Cloudy areas receive even less sunlight. During winter, some people may see the sun for such a short time that they become depressed. This is not just sadness about short days; it is apparently the result of hormone levels that are influenced by sunlight. Treatment may include use of lights that mimic the spectrum of daylight along with anti-depressants or talk therapy.

Wind is caused by unequal heating of different areas. Recall from Chapter 3 that warmer air will have a lower density than cold air, so warm air rises while cold air sinks. As the warm air rises, it causes a low pressure zone. Colder air is pushed into these areas from colder, higher-pressure areas. Because the difference between temperature in different areas might be fairly consistent, wind direction might also have a consistent trend, even though there may be a lot of short-term variation in wind speed and direction. Wind from a warmer or colder area can raise or lower local temperatures.

**Misconception Alert: Wind always cools objects.**

**FALSE.** Wind increases the rate at which heat is moved. If you put your hot coffee mug in front of a fan, it will cool faster because the fan is constantly pushing cooler air next to the mug and pushing away the warmer air. You can leave your coffee in front of the fan all day and it will not get any cooler than the temperature of the air.

So why do you get colder on a cold day when the wind blows? Your body is usually warmer than the air and is constantly producing heat. If the air around you is fairly still, you are surrounded by that warmer air. When the wind is blowing, it is constantly moving that warmed air away and hitting you with cold air. That's called wind chill.

Sometimes wind warms an area. The chinook winds of northwestern North America carry warm dry air that speed up spring snowmelt.

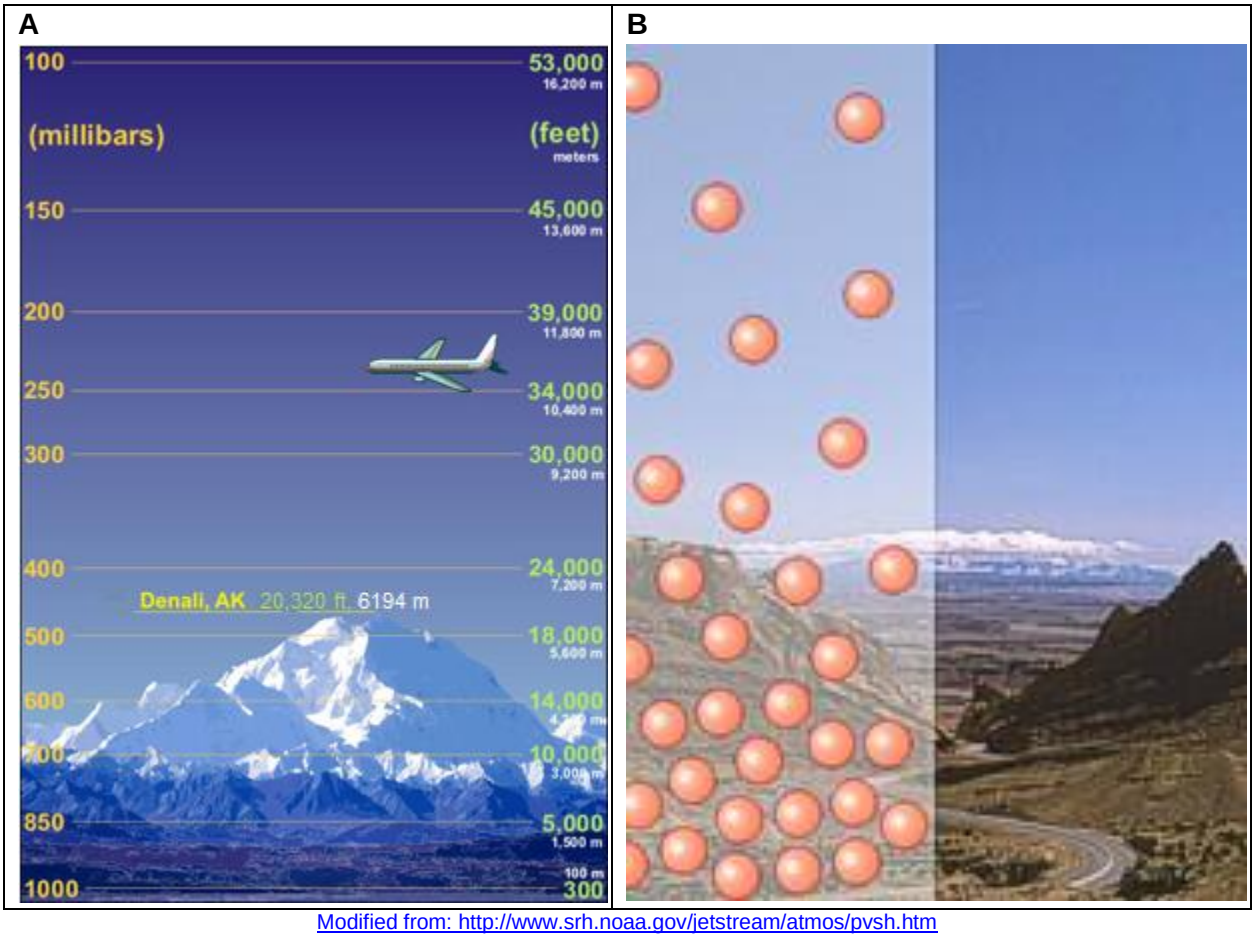
**Check Your Understanding**

- Describe some ways that heat can move through the environment
- Explain why areas get more extreme seasons if they are far north or south of the equator.

**Elevation Influences Climate**.

Recall from Chapter 3 that gas has mass. Imagine the column of air above your body. It extends to the limit of our atmosphere. If you are higher up (at a higher elevation), that column of air is smaller, and exerts less pressure (Figure 6). The air is more compressed close to sea level

because the column of air is taller and heavier. Where jets fly, you are much closer to the top of the air column, so there is less mass compressing the oxygen molecules in the air close together. There are fewer oxygen molecules in a lungful of air. To give people enough oxygen, air is forced into the cabin of a jet, squeezing those molecules together. If the cabin of a high-flying jet loses pressure, you need supplemental oxygen.




Modified from: http://www.srh.noaa.gov/jetstream/atmos/pvsh.htm

Figure 6. The influence of elevation on air pressure and density of gases. **A** Air pressure in millibars is shown in yellow on the left. Elevation in feet (green) and meters (white) is shown on the right. **B** The red circles are used to show that molecules (such as oxygen) are closer together where pressure is high.

**Analyze the Figure**

- As elevation increases from 100 m to 3,000 m, what happens to air pressure in millibars?
- Why might climbers use supplemental oxygen on the top of Denali?

Air cools as it expands because the same amount of energy is spread into a larger volume. Higher elevations are cooler than lower elevations at the same latitude (Figure 7). High mountains often have glaciers (ice layers that do not disappear in summer).

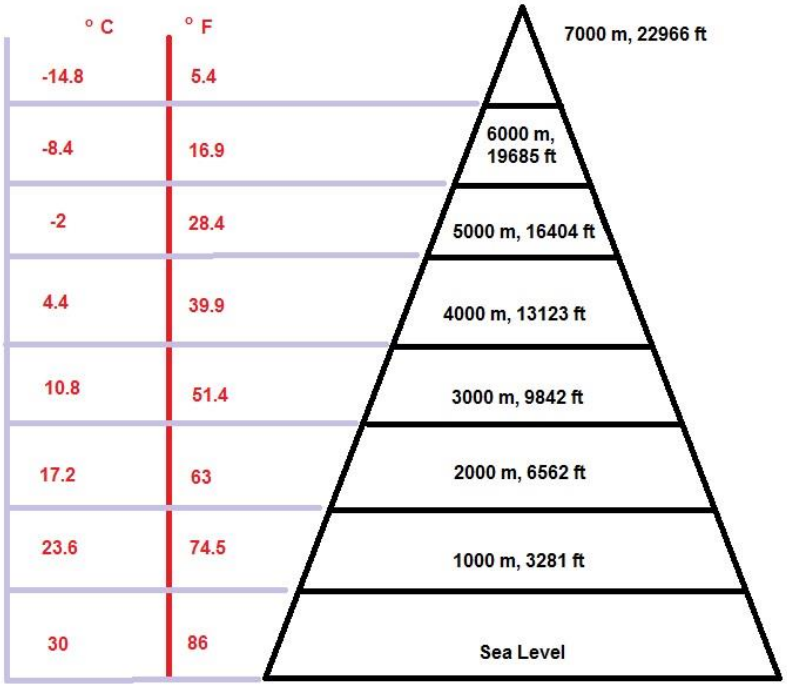



Figure 7. As distance above sea level increases, temperature decreases. If the temperature at sea level is about 30 ºC (86 ºF), it will be about -14 ºC (5.4 ºF) at the top of a high mountain (over 6000 m) in the same area.

**Analyze the Figure**

- Assume that the air temperature is 30 ºC at sea level. As elevation increases to 3,000 m, what happens to the temperature?
- Why are there glaciers on the top of Denali?

**Check Your Understanding**

- Explain why air pressure is higher near sea level than above it.
- Explain why high-elevation areas are colder than low-elevation areas.

**Proximity to Water Influences Climate**

As described in Chapter 3, water can store a lot of heat (it has a high thermal inertia). Heat can be transferred between air and water, but air requires less heat movement to change temperature. When the air is warmer than the water, some of that heat is transferred to the water. When the air is cooler than the water, the heat in the water warms the air. Areas near oceans or large lakes usually have more moderate temperatures as a result. Ocean currents

move cold and warm water around the globe, influencing land temperature. This will be discussed more in Chapter 9.

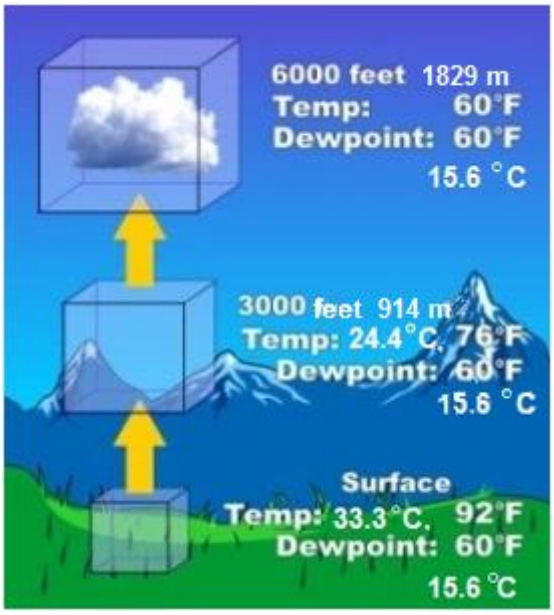
Areas near water generally have more **humidity**, or water vapor in the air due to evaporation. People often speak of warm air "holding" more water. While this is not technically true, it is a good way to remember that **relative humidity** depends on air temperature. When temperatures are warmer, more of the water molecules in an area will be in the gas (vapor) state. Clothes driers demonstrate this. They use heat to increase evaporation of water from clothes, then blow the warm, wet air away. Bringing air into a drier is important because when the air is saturated with water, evaporation stops.

When air cools, the relative humidity increases. Eventually the water vapor will condense into liquid water. The temperature at which this happens is called the **dewpoint**. The dewpoint is higher when there is more humidity and lower when there is less humidity.

**Make the Medical Connection: Dewpoint and Heat Illness**

Normally, sweating helps to cool your body because water has a high thermal inertia. Heat from your skin is causes evaporation of the water in sweat, which results in less heat on your skin. If you have spent time in a humid climate, you know that sweat does not evaporate well at high humidity because the air is already saturated with water. When sweat doesn't evaporate, it doesn't cool the body. Some weather reports include a heat index to warn people when the temperature and dewpoint are high, increasing the risk of heat illness.

Recall that warm air expands and cools as it rises (Figures 6 and 7). When it cools to the dewpoint, water vapor can condense on dust particles in the air to form clouds. If enough water condenses, precipitation will fall.




Modified from: http://www.erh.noaa.gov/iln/research/dec2011clouds/index.php

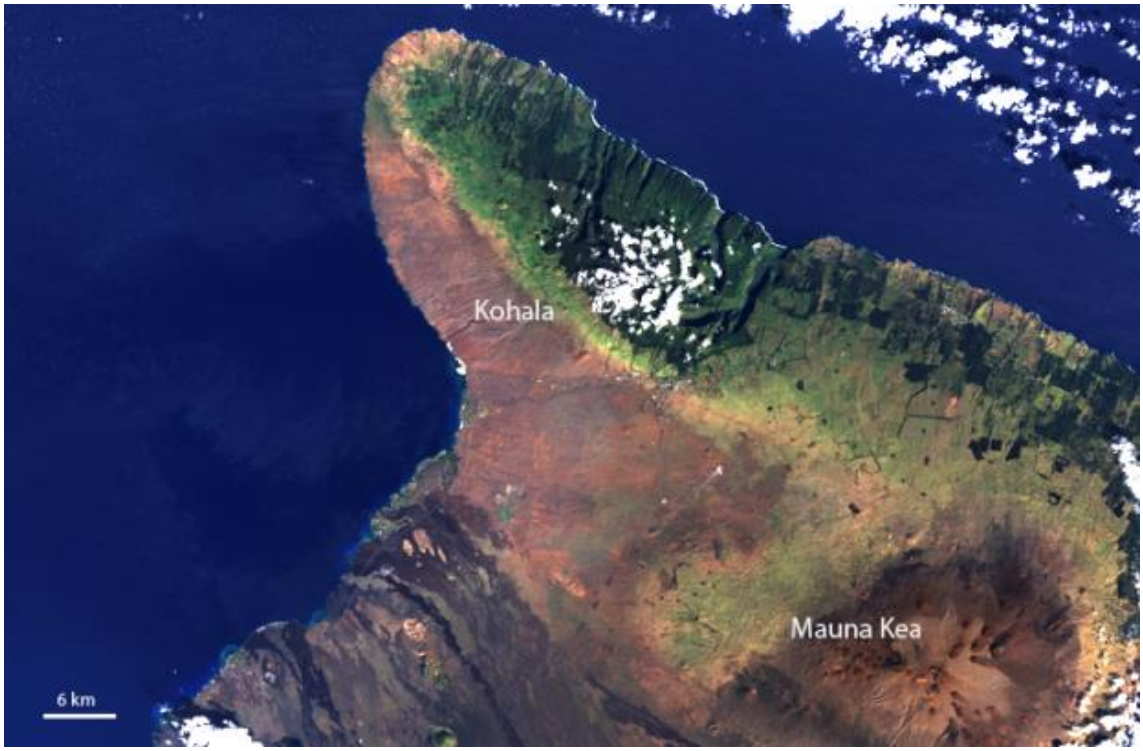
Figure 8. Air expands and cools as it rises. Dewpoint is the temperature at which it will condense. Water condenses on dust particles in the air, forming clouds.

**Analyze the Figure**

- Why are the cubes larger at higher elevations?
- Why don't clouds form at 914 m/3000 feet (in this example)?
- Does temperature influence the dewpoint?

Near the equator, there is a lot of energy entering as sunlight, causing evaporation, especially over bodies of water. Temperatures near the ground may be warm or hot, but the temperatures high above sea level will be much cooler than at ground level, as shown in Figure 7. The cooling of rising, humid air can result in heavy rains in the tropics. Air rising over mountains can also lead to heavy precipitation on the side facing large bodies of water.

Once water has precipitated out of the air, there is little humidity left for locations further downwind from the source of the water. This can result in a dry area, called a **rain shadow**, on the downwind side of a mountain (Figure 9).



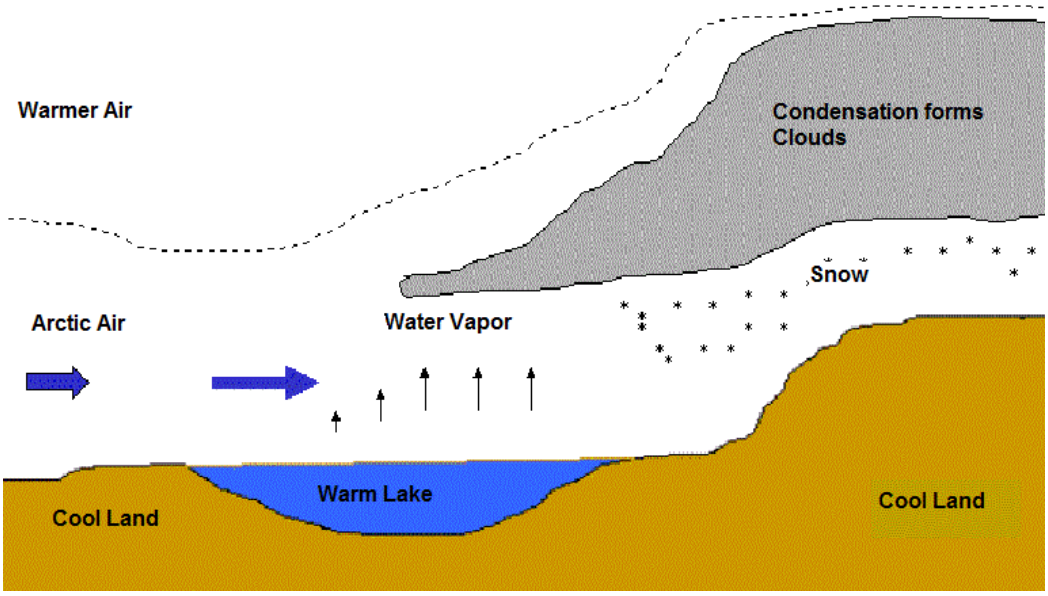

http://www.climate.gov/news-features/featured-images/rain-shadows-summits-hawaii

Figure 9. Satellite image showing a rain shadow on the eastern side of Kohala on Hawaii's Big Island. The winds blow from the northeast. Warm air rises on the slopes of Kohala and cools. Water condenses as rain. Green shows vegetation.

**Analyze the Figure**

- Why are the two sides of the island so different?
- If the winds were from the southwest, what pattern would you see?

Because of thermal inertia, a lake in winter is usually warmer than the surrounding land. If wind blows across bodies of water, it gains heat and water vapor. This relatively warm, wet air can flow over cooler land areas, resulting in heavy **lake effect** snow as the humidity in the air condenses and freezes (Figure 10). Very cold air is usually very dry because there is so little heat available to evaporate moisture. This is why it snows very little on extremely cold days.




Modified from: http://www.erh.noaa.gov/bgm/WeatherEvents/Snow/oceaneff/slide6.html

Figure 10. Lake effect snow happens when water evaporates into the atmosphere over a lake, then condenses and freezes over cold land areas. In this figure, winds are blowing from the west and the area receiving the snow is to the east of the lake. In the USA, Eastern Michigan and New York State receive lake effect snow often.

**Analyze the Figure**

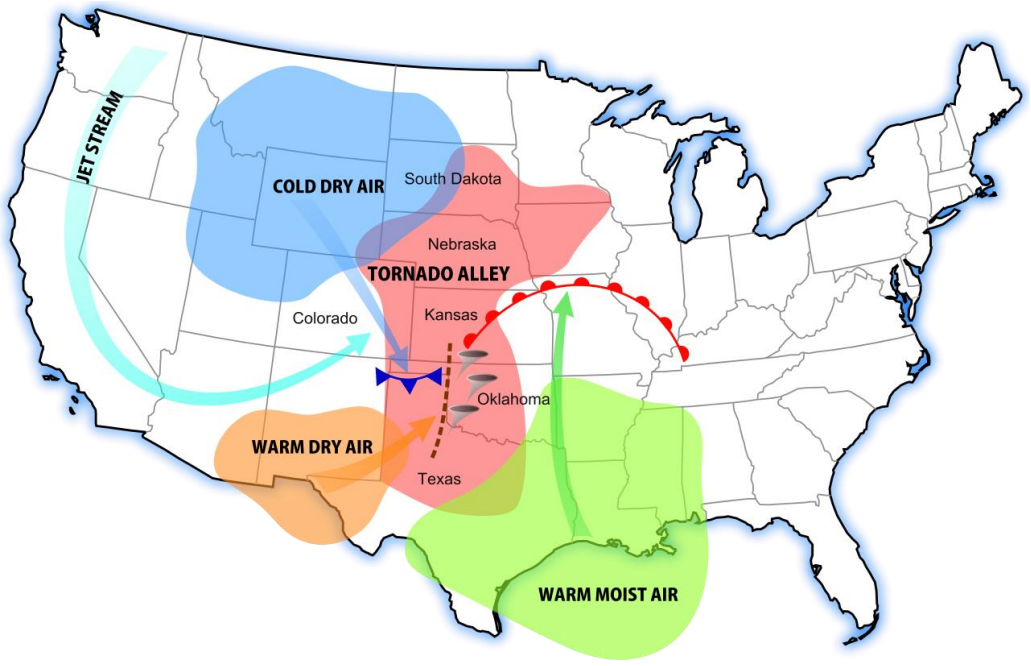
- What makes the water vapor condense?
- Why is the lake warmer than the land?
- If the winds were from the east, what pattern would you see?

You may be wondering why the higher air mass is warmer after learning that air cools as it rises. Masses of cool and warm air move across the landscape and interact. In this example, a denser cold air mass pushed a warmer air mass up. It can take some time for the warmer air to cool.

**Check Your Understanding**

- Explain how thermal inertia influences the climate of areas near large bodies of water.
- Explain what causes rain shadows.
- Predict whether relative humidity will increase or decrease when temperature increases.

**Case Study Part 2. What causes Tornadoes?**




http://en.wikipedia.org/wiki/Tornado_Alley#/media/File:Tornado_Alley_Diagram.svg

Figure 11. Factors that cause tornadoes. These same conditions could occur in other places. The line with blue triangles shows a cold front, the front edge of a moving mass of cold air. The line with red half circles shows a warm front. The brown dashed line shows where tornados are likely to form.

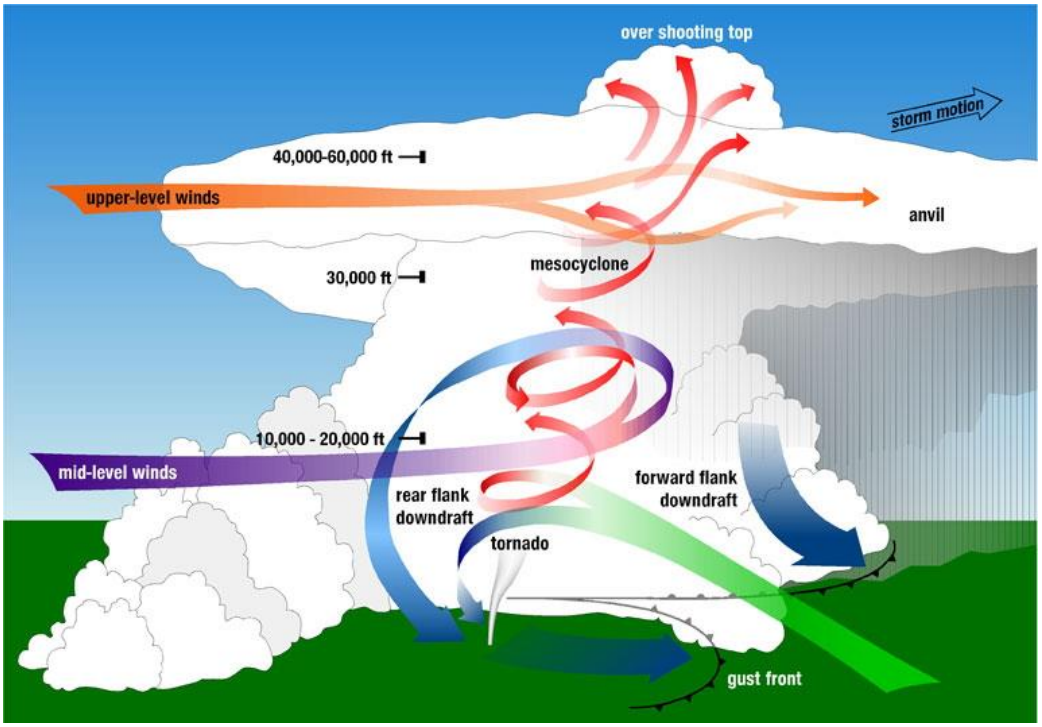
**Analyze the Figure**

- What are the sources of the warmer and cooler air masses?
- Which direction are the fronts moving?
- Would the air masses, fronts, and jet stream always be in the same places? Explain your answer.

In late spring and early fall, tornadoes often form in the area nicknamed tornado alley (Figure 11), but they can form at other times and places, as the Joplin tornado shows. Tornadoes contain huge amounts of energy. The ultimate source of the energy is the Sun, which heats different areas unequally. As discussed in Chapter 3, warm air is less dense than cold air, so it rises. Interactions between air masses with different temperatures cause wind. These winds are particularly strong high in the atmosphere, creating a sort of river of wind called a jet stream.

When the warm moist air from the Gulf of Mexico meets the cool, dry air from the northwest, the warm air is driven up because it is less dense. As the warm, moist air rises, multiple things happen. First, the air cools, and moistures starts to condense on dust, forming clouds. Rain may start to fall, but strong upward flow of warm wind can push the drops back up into colder air

where they freeze as hail. If there is enough warm air, the same drops can be driven back up several times, growing each time.




https://www.weather.gov/iwx/2013_straight-line_winds_vs_tornado

Figure 12. How supercells form and lead to tornadoes. Warm, moist air meets cool, dry air and rises very rapidly. Cool air falls rapidly. As the base spins, tornadoes can form.

As the air moves up, it creates a low pressure zone. This means that air is “filling in” behind the rising warm air. The more heat in the air mass, the higher it rises. These storm clouds can reach high up into the atmosphere—over 20,000 meters—creating huge storm clouds. As the air reaches the stratosphere, it spreads out, causing the feared “anvil cloud” (Figure 12). The rising air can move over 150 km/hour. The cooling air also falls quickly. A large system called a storm cell or supercell forms with columns of warm air rushing up the center and cold air falling outside it. If everything were perfectly stable this system of rising and falling air would stay in one place, but that rarely happens. There are usually winds coming in from the side, such as the jet stream. This can start the column spinning. If the bottom becomes narrow, all of the energy is concentrated into a small area, causing faster and faster spinning. If this cone of spinning air touches the ground, it is a tornado.

A satellite image from Joplin Missouri on May 22, 2011 shows the anvil-shaped cumulonimbus clouds from above (Figure 13). To the east are cirrus clouds that indicate a jet stream in the upper atmosphere. This dangerous combination led to the devastating tornado. Tornadoes are rated from 0 to 5 by their wind speed (Figure 14). The Joplin 2011 tornado was an EF 5 with winds of at least 322 kilometers per hour (200 miles per hour) at its strongest.

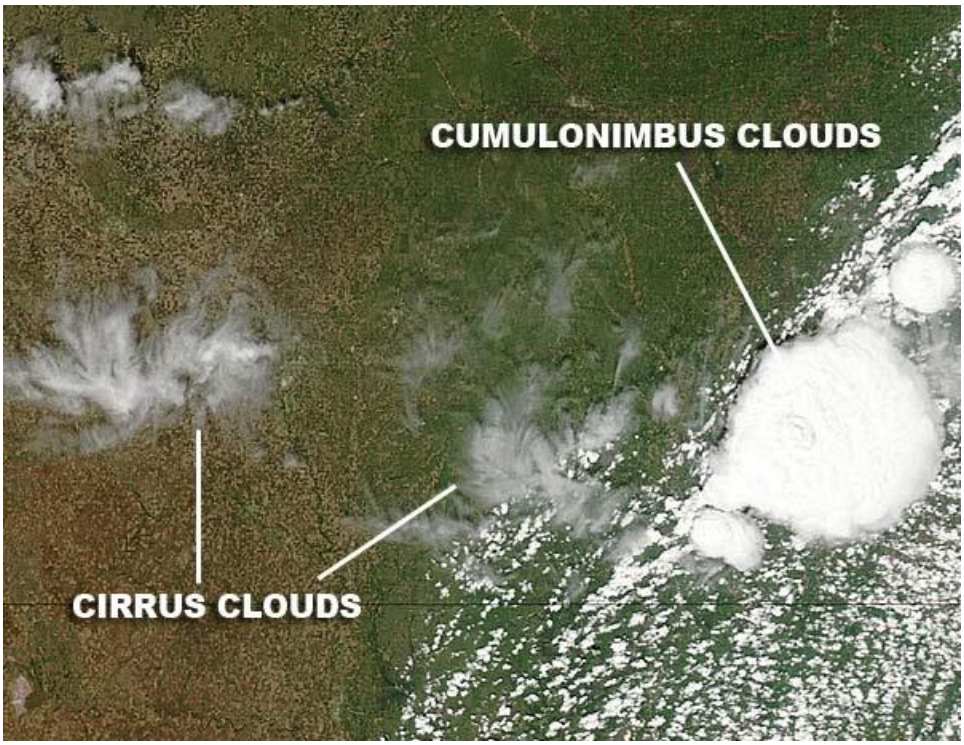



Image credit: NASA/GSFC MODIS Rapid Response
http://wwworigin.weather.com/outlook/weather-news/news/articles/meteorological-images-2011_2011-12-30?page=4

Figure 13. Satellite image from near Joplin, MO on May 22, 2011. On the right is a supercell of cumulonimbus clouds formed by warm, moist air meeting cool, dry air. On the right and in the center are cirrus clouds formed by a jet stream.

**Misconception Alert: A slight change in average global temperature won't change much on Earth.**

**FALSE.** A small change in average temperature is enough to alter sea level, change growing seasons, and influence whether precipitation falls as rain, snow, or not at all. It can provide more energy to major storms, increasing the frequency and severity of tornadoes and other dangerous weather. It can also shift ranges of species (see Chapter 10).

| EF Rating | Wind Speeds | Expected Damage | | |
|---|---|---|---|---|
| EF-0 | 65-85 mph | 'Minor' damage: shingles blown off or parts of a roof peeled off, damage to gutters/siding, branches broken off trees, shallow rooted trees toppled. | | |
| EF-1 | 86-110 mph | 'Moderate' damage: more significant roof damage, windows broken, exterior doors damaged or lost, mobile homes overturned or badly damaged. | | |
| EF-2 | 111-135 mph | 'Considerable' damage: roofs torn off well constructed homes, homes shifted off their foundation, mobile homes completely destroyed, large trees snapped or uprooted, cars can be tossed. | | |
| EF-3 | 136-165 mph | 'Severe' damage: entire stories of well constructed homes destroyed, significant damage done to large buildings, homes with weak foundations can be blown away, trees begin to lose their bark. | | |
| EF-4 | 166-200 mph | 'Extreme' damage: Well constructed homes are leveled, cars are thrown significant distances, top story exterior walls of masonry buildings would likely collapse. | | |
| EF-5 | > 200 mph | 'Massive/incredible' damage: Well constructed homes are swept away, steel-reinforced concrete structures are critically damaged, high-rise buildings sustain severe structural damage, trees are usually completely debarked, stripped of branches and snapped. | | |

https://www.weather.gov/shv/awarenessweek_severe_tornadoes

Figure 14. The Enhanced Fujita Scale describes the severity of tornadoes. The 2011 Joplin tornado ranged from EF-0 to EF-5.

The location, timing, and severity of storms such as tornadoes depends on factors such as the amount of heat and water available and whether air masses with different temperatures meet. These factors are determined by latitude, elevation, topography, and location of bodies of water.

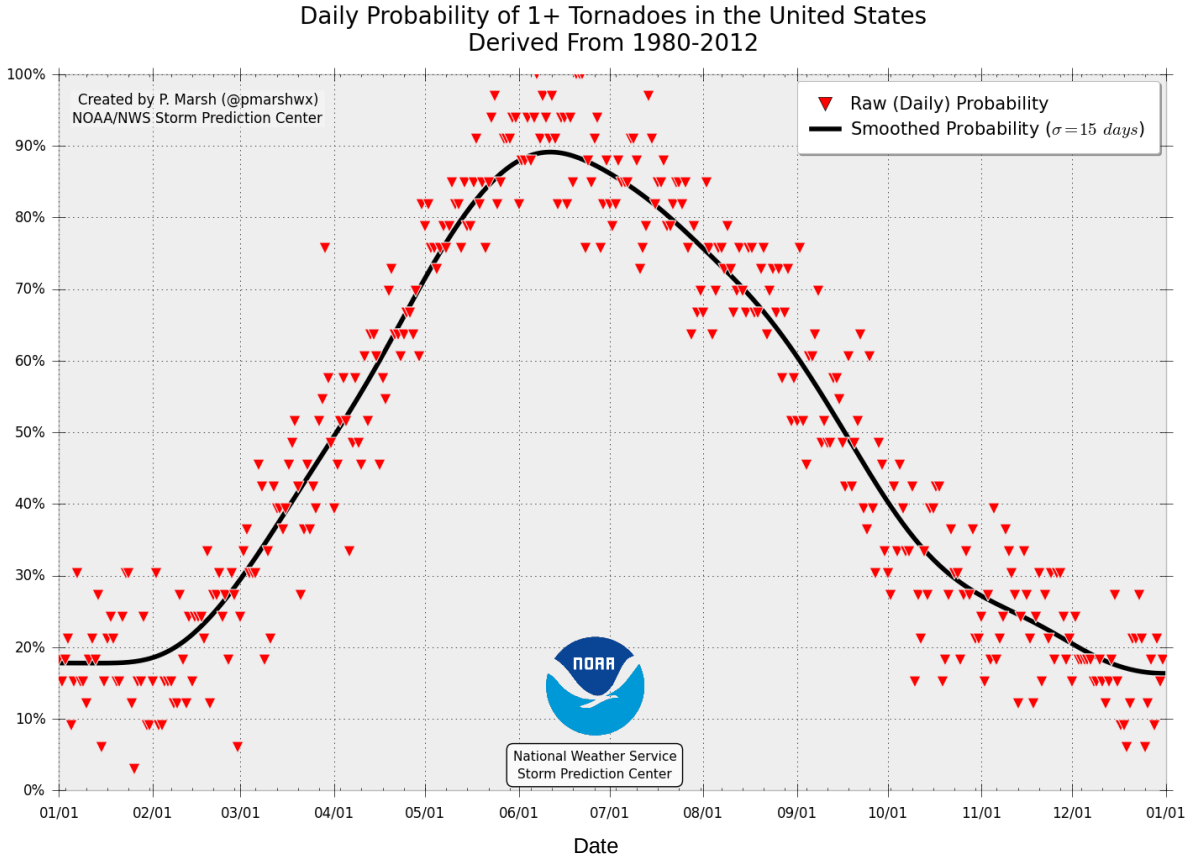
Hurricanes (also called typhoons) have similar causes, but they form over water. After they make landfall, they start to lose their power, so they do not usually go very far inland. They can be devastating along the Atlantic Coast of the USA.

**Learning from the Case Study**

- Why don't very dry or cold places have tornadoes?
- Why does hail (ice) fall in the summer when it's hot?

**Model Skill: Line charts**

Line charts are used to show change through time. The time scale (such as days, months, or years) is usually on the X-axis and the dependent variable is on the Y-axis. Day-to-day variation can be high, so data for a longer time period is often averaged to emphasize general patterns over daily variation.




https://en.wikipedia.org/wiki/File:US_daily_tornado_probability.png

Figure 15. The National Weather Service used historical data (1980-2012 in this case) to compute an average daily risk of at least one tornado occurring in the United States. The red triangles show the daily risk, the lines show the average probability over 15 days. Dates are written as month/date. For example, 05/01 is the first of May.

**Analyze the Figure**

- What month has the highest probability of tornadoes in the USA?
- Is there a month when there is no chance of a tornado in the USA?
- Why is the pattern of line “smoother” than the pattern of triangles?

**Using Weather Data to Analyze Climates**

Most locations where people live (and many where they don't) have regular weather monitoring. We can use long-term average temperature data to look at annual climate patterns in a particular area (Figure 16; see **Model Skill: Line charts** for help in understanding the figure).

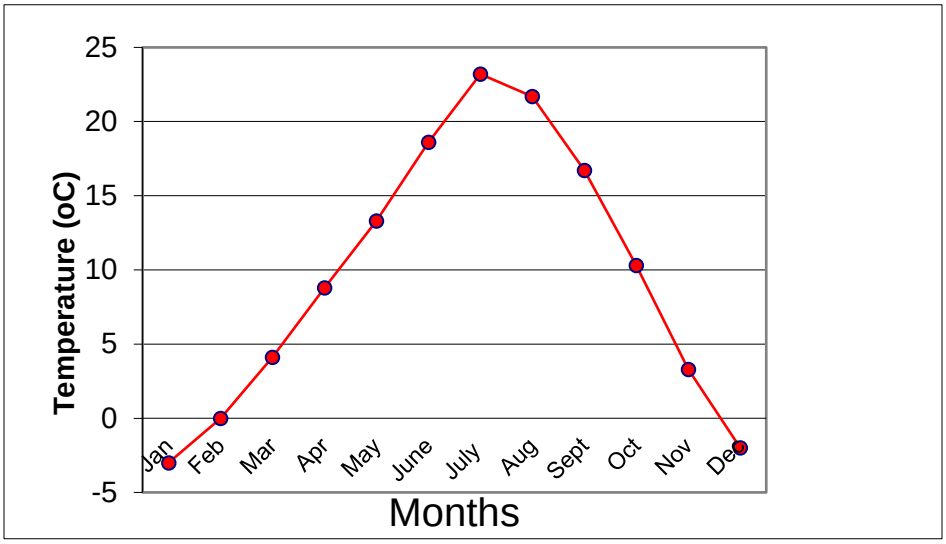



Figure 16. Long-term average monthly temperatures in one location.

**Analyze the Figure**

- Which months are especially warm or cold?
- How many months have a minimum average temperature at or below freezing?
- What is the maximum average monthly temperature?

What can we infer from the data? Because the coldest months are January and February, we can infer that this location is in the Northern Hemisphere. Because the temperature varies a lot, we can infer that it is not close to the equator. Plants need liquid water for photosynthesis. Because three months are at or below freezing, we can infer that the growing season will be roughly nine months. When might snow fall in this area? Keep in mind that these numbers are averages. If the average monthly temperature in November is 3 $^{o}$C, the temperature may drop below freezing many times, and some days may be a lot warmer.

To get a clearer picture of the climate, we need information on precipitation. We can add a second Y-axis to the same graph (Figure 17). This climate graph has a very specific format for the two Y-axes. When the temperature line is above the precipitation line, we can infer that water losses due to evaporation are higher than water input from precipitation. In other words, it indicates a dry season. This is not the same thing as a drought. A drought is an unusually dry period compared to what is normal for a particular place and time. Dry seasons are part of the normal annual cycle in some areas.

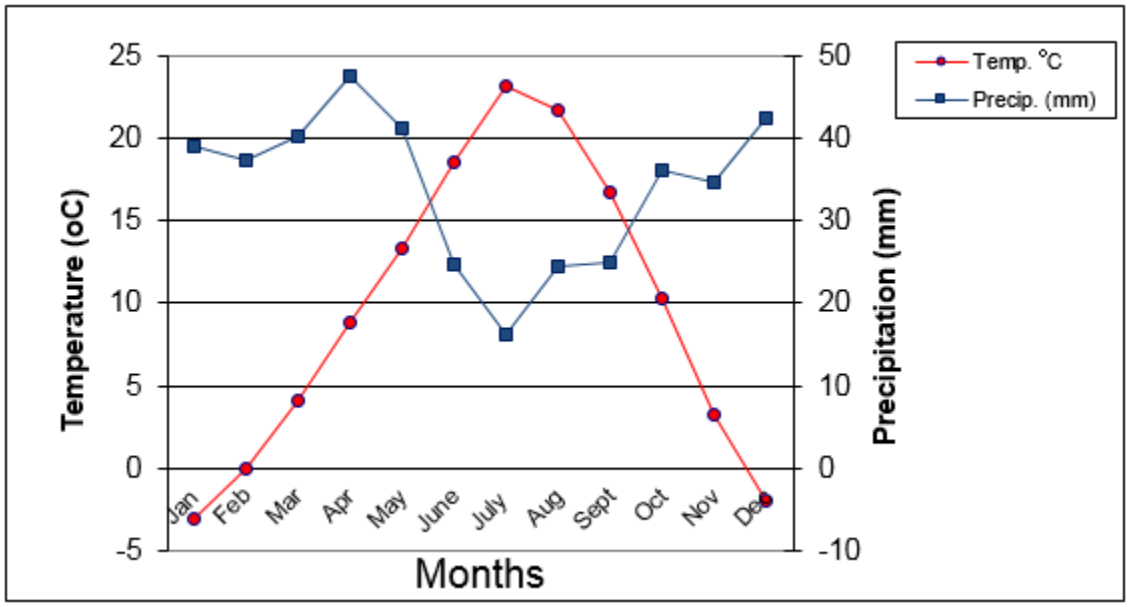



Figure 17. Long-term average monthly temperatures and average total monthly precipitation in one location. The annual average temperature = 9.6 $^{o}$C. Total annual precipitation = 409.7 mm. The zeros align and every 5 $^{o}$C on the left Y-axis is matched by a 10 mm increase in precipitation on the right Y-axis.

**Analyze the Figure**

- What is the general pattern of precipitation in this area? Is it seasonal? When is precipitation especially high or low?
- When is there a dry season (precipitation line is below the temperature line)?
- When might this area receive snow?

Climate graphs that include precipitation allow us to improve our inferences about the length of the growing season. In the location shown in Figure 17, we can observe a summer dry season. However, if this area receives a lot of snow, snow melt may provide water even when rain is not falling. This could extend the growing season. On the other hand, plants may still be covered with snow when the temperature is well above freezing. The highest average monthly precipitation is about 48 mm. Precipitation is measured in the liquid state and snowflakes take up a lot more space than liquid water, so the average snowfall in March is over 600 mm. The location in Figures 16 and 17 is Park City, Utah, USA—the site of the Winter Olympics in 2002.

Climate influences wildfire risk. Fires need fuel. Locations that are very hot and dry produce few plants, so fires cannot spread. Locations that stay very wet all year rarely burn. Locations where there are good conditions for plant growth during some seasons, followed by hot, dry conditions are usually prone to fires. Does Park City have conditions that might lead to fire? When might those fires occur?

Park City is located at about 40 degrees north latitude. If you were trying to infer where this location is, you may have assumed it was closer to the North Pole than the Equator because of its low winter temperatures. Park City is also is located 2100 m above sea level, so it is colder than you might expect if you only knew the latitude. Chapter 8 will discuss climate zones further. To explore these charts in more detail, see **Taking it Further: Making a climate graph**.

**Taking it Further: Making a climate graph**

Climate graphs efficiently summarize a lot of information about an area. They are based on averages, which means that variation is hidden, but this also makes general trends easier to see.

The first step in making a climate graph is to find long term average monthly temperatures and precipitation levels for a particular place. Use average monthly temperatures, not average minimum or maximum temperatures. Use a data set collected over 10 or more years to describe the climate. (You could compare two different years to see how the weather differed between years.) Also note the annual average temperature and the average annual total precipitation. Convert the units if necessary. Precipitation should be in mm. Temperature should be in degrees Celsius. Use the data to fill in a table similar to Table 1.

Table 1. Form for gathering climate data.

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp. $^{o}$C | | | | | | | | | | | | | |
| Precip. mm | | | | | | | | | | | | | |

Next, note the maximum and minimum average monthly temperatures and the maximum monthly average precipitation level. These will determine the scale of the Y-axes on your graph.

Both of your Y-axes must have the same point for zero. The minimum temperature value will determine the minimum Y-axis value. Every one degree C difference in temperature is matched by a two mm difference in precipitation. Determine which is greater, the maximum temperature in $^{o}$C or half the highest monthly precipitation. The greater number will determine the maximum necessary Y-axis value. It is common to have the axis values in increments of 10, so an axis might be set from 0 to 40 to accommodate a temperature range of 7 $^{o}$C to 38 $^{o}$C (Figure 18).

**Continued**

**Taking it Further: Making a climate graph, cont.**

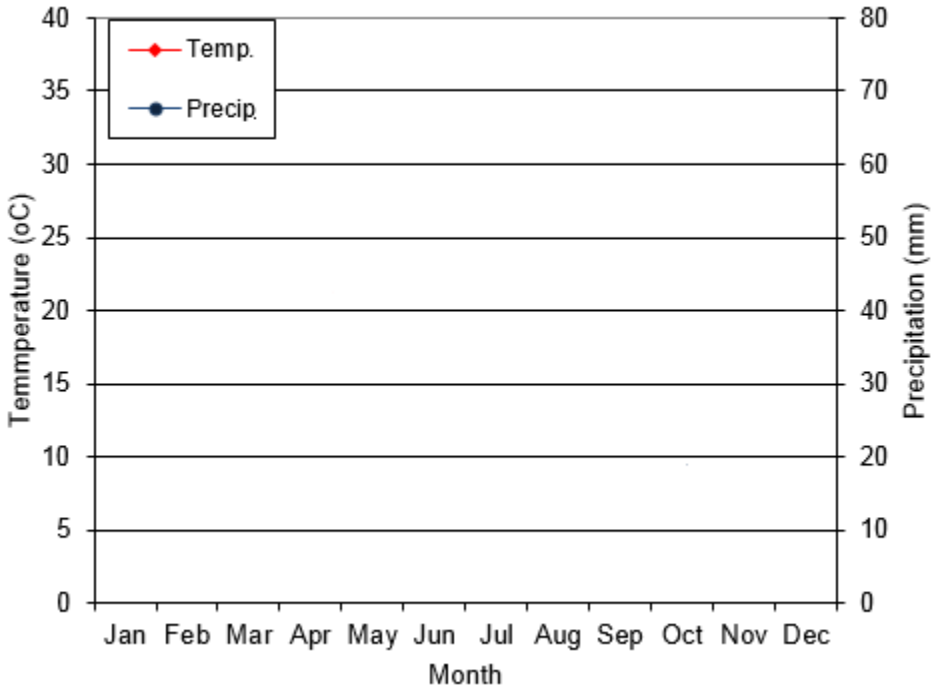



Figure 18. Blank climate graph that would accommodate data for a location with a minimum average monthly temperature of 0 ºC or greater, a maximum average monthly temperature of 40 ºC or below, and a maximum average monthly precipitation of 80 mm or less.

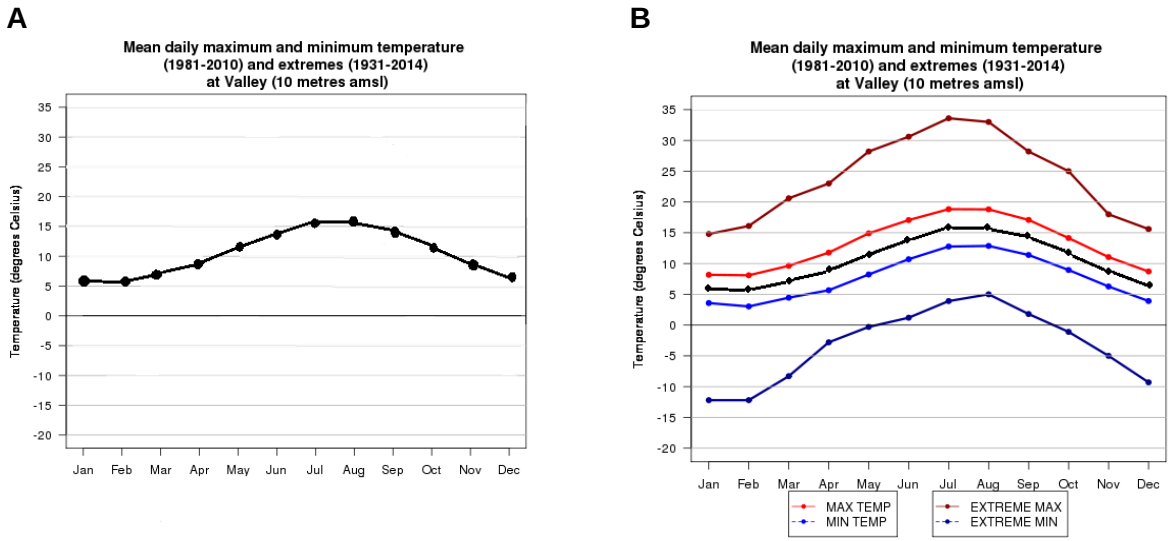
If the range were greater, it might be necessary to make the intervals longer (for example, 10 or 20 ºC between each interval instead of 5 ºC). Each ºC must still correspond with 2 mm of precipitation.

Plot the data for temperature using one line and the data for precipitation using another. The lines should either be different colors or have different lines or data point markers to avoid confusion between the two data sets. The legend should allow the reader to identify the lines.

The total mean precipitation and average temperature for the year are sometimes listed on the graph. The elevation in meters or the latitude and longitude may also be included. More examples of climate graphs are presented in Chapter 8.

Climate graphs—like any models—simplify complex systems. Each dot on a climate graph's temperature line is an average of the temperatures all day, for every day in that month, over many years. Looking at the mean monthly temperatures for Valley, Wales, UK (Figure 19 A) might give you the impression that the temperature never goes below freezing. However, a

graph that includes average minimum and maximum temperatures, and extreme temperatures (Figure 19 B), provides a clearer picture of the variation around the mean.




Modified from: http://www.metoffice.gov.uk/climate/uk/regional-climates/wl

Figure 19. Temperatures for a town in Wales (amsl = average meters above sea level). **A**. Mean temperatures averaged over entire days, throughout the month, over many years. **B**. The same graph with average minimum and maximum monthly temperatures and extreme temperatures added.

**Analyze the Figure**

- How many months never had an extreme temperature below 0 $^{o}$C between 1931 and 2014?
- Compare the extreme maximum temperature in January with the extreme minimum temperature in August. Which is higher?

**Check Your Understanding**

- Describe how one can identify a dry season on a climate graph.
- Explain how a climate graph can be used to estimate the length of the growing season.
- If a region has its lowest temperatures in July and August, in which hemisphere is it? Explain your reasoning.

**Small Scale Conditions Create Microclimates**

The weather forecast for your area gives a general picture of what you can expect. However, actual conditions may be very different in the middle of a parking lot, under a tree, on the sunny side of a building, or inside your home. **Microclimates** are the result of localized differences in factors that influence temperature, humidity and wind (Figure 20). You know that shade usually causes cooler microclimates. You also know that both natural and human-made objects can block wind. Other factors can also be important.

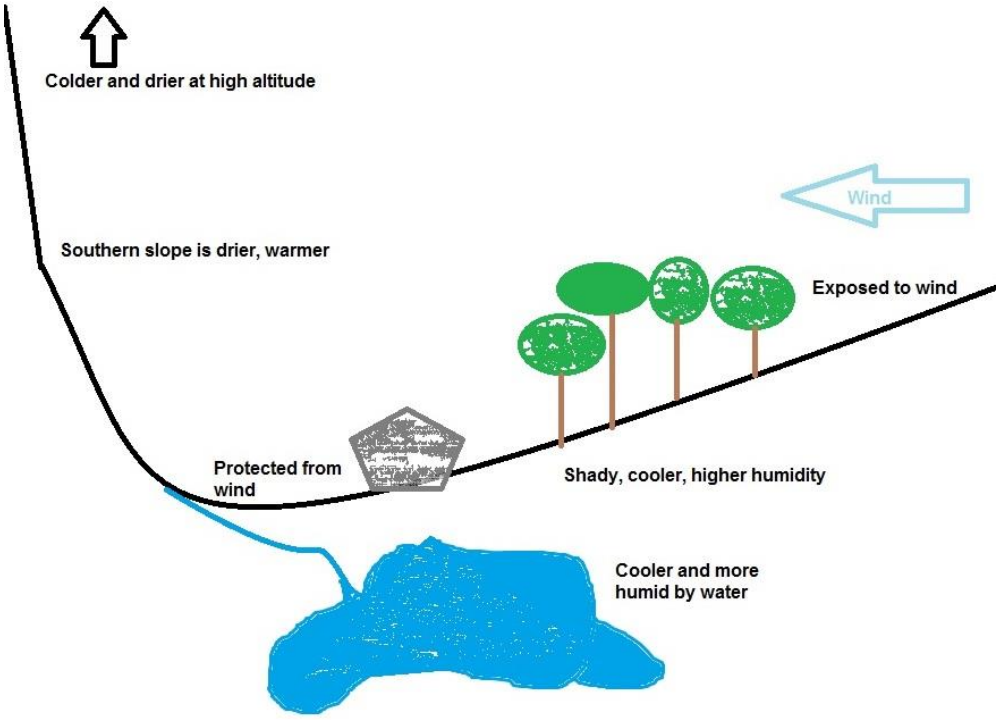



Figure 20. Microclimates are small-scale climates influenced by factors such as aspect, shade, color, vegetation, and proximity to water.

**Analyze the Figure**

- What factors shown in the figure will influence the temperature of various small areas?
- What factors shown in the figure will influence the humidity of various small areas?
- How might these factors influence plant growth or animal movements?

Vegetation influences microclimate by providing shade. It can also raise humidity as water evaporates off the leaves. As discussed in Chapter 5, evaporation requires energy, cooling the surfaces where evaporation occurs. Vegetation can block wind as well, especially if the vegetation is large, or there is a lot of it. For more on how vegetation creates microclimates, see **Hypothesis Testing: Do Live Oaks Create Favorable Microclimates for Other Plants?**

The type of **substrate** (ground) might be rock, dry sand, moist soil, frozen tundra or manufactured material. All of these substrates may influence temperature or humidity. For example, rock and concrete have high thermal inertia. They take a long time to heat up, but will continue to radiate heat when the air temperature cools. Moist soil can create a zone of higher humidity than that above dry sand.

The air temperature is usually measured at 1.5 m above the ground because some soil can be much hotter than the air temperature. The color of the substrate will influence how much light is reflected and how much is absorbed and given off as heat. Lighter colors reflect more light than dark surfaces. Snow can actually reduce the temperature in an area because it causes more

light to be reflected than absorbed. This can cause a positive feedback loop. When an area is covered by snow, more light is reflected, so less snow melts.

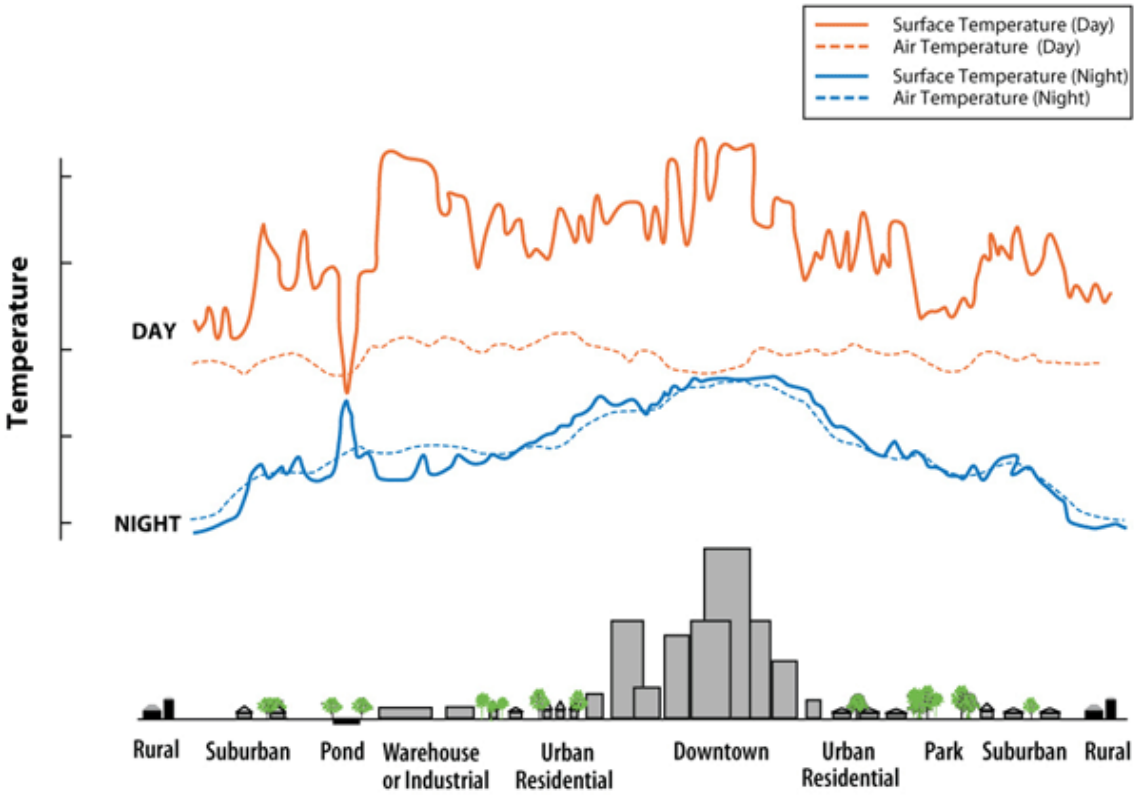
**Aspect** refers to the direction a slope is facing. A hillside in the Northern Hemisphere that faces south will get more sun than one that faces north because the sun will be closer to the southern horizon for much of the year. The east side of a tree or a building will get morning sun and afternoon shade.

These variations in microclimate help to explain why plants that can't survive in the open desert can thrive under the shade of a palo verde tree, or why the trees that grow on the south slope of a mountain are different from those found on the north slope. To learn how understanding microclimates can improve energy consumption and quality of life in urban areas, see **Why it Matters: Heat Islands**.

**Why it Matters: Heat Islands**

On a hot day, will you be cooler on a park lawn or in an urban parking lot? Factors influencing microhabitat (substrate, color, etc.) make urban and industrial areas hotter than rural or park-like areas on hot days (Figure 21). Pavement, concrete, and other manufactured materials can absorb a lot of heat during the day. There may be fewer bodies of water around to allow evaporative cooling. Tall buildings may block wind that would move the hot air out of urban areas. Vegetation that could cool the area through shading and evaporation are often rare.

Some cities are encouraging the use of urban plantings, green roofs (which grow plants), reflective roof and pavement materials, and other mitigations to decrease the urban heat island effect.




http://www.epa.gov/hiri/images/UHI_profile-rev-big.gif

Figure 21. Temperature profile indicating how different types of natural or human-constructed objects can influence small-scale climate.

- Why would urban heat islands be a public health issue?
- How would heat islands influence energy used during peak times on summer days?
- What are some other potential benefits or costs of increasing green spaces in cities?
- Should new or existing buildings be required to reduce the heat island effect?
- Lower income areas often have less green space. Why might this be an environmental justice issue?

**Hypothesis Testing: Do Live Oaks Create Favorable Microclimates for Other Plants?**

https://tpwd.texas.gov/education/hunter-education/online-course/wildlife-conservation/texas-ecoregions

Figure 22. Plateau live oak trees (*Quercus fusiformis*) junipers, and other plants on the Edwards Plateau in central Texas.

Both biotic and abiotic variables can create microclimates that allow species to colonize an area. Some large plant species may act as **nurse plants** in hot, dry climates. Nurse plants create microclimates that have higher moisture and lower temperatures than the surrounding area. The shade of nurse plants can decrease both air and soil temperatures, which can decrease evaporation from the soil and from plants below the nurse plants. The roots of trees can also bring moisture from deep in the soil to soil nearer to the surface. By creating favorable microclimates, nurse plants may create suitable habitat for other species in areas that would otherwise be too hot and dry.

Gass and Barnes (1998) were interested in whether plateau live oaks facilitate the growth of Ashe juniper (*Juniperus ashei*) and other plants in a semi-arid region of central Texas, USA (Figure 22). The oak trees grow in clusters that have an understory of shrubs and non-woody vegetation. These clusters are surrounded by grassland. The canopy is the extent of the branches.

Hypothesis: Live oaks act as nurse plants, allowing shrubs to establish and grow under them.

It is reasonable to expect that shading, air temperatures, and soil temperatures would vary greatly on different sides of a stand of oak trees, particularly in the summer, when solar inputs are highest. Researchers measured air temperatures at each of the cardinal compass points

(north, east, south, and west) around ten oak clusters (Figure 23). They also measured soil temperature and the amount of light entering. They found that soil temperature was greater than air temperature to the south and west, but lower than air temperature on the north and east. The lowest shading was on the west side, and the most shading on the east side.

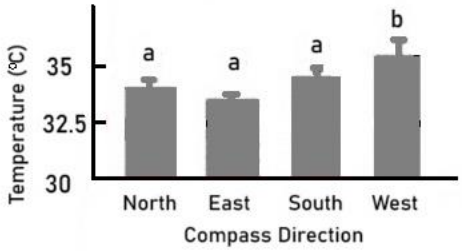



Figure 23. Air temperature on different sides of a cluster of live oaks. Different letters indicate a significant difference. Modified from: Gass, L., & Barnes, P. W. (1998). Microclimate and understory structure of live oak (Quercus fusiformis) clusters in central Texas, USA. *The Southwestern Naturalist*, 183-194.

**Analyze the Figure**

- Which direction had the highest temperature?
- How would the direction of the sun throughout the day explain this pattern?
- Do these data support the hypothesis, partially support the hypothesis, or refute the hypothesis? Explain your answer.

Researchers measured temperature (Figure 24), shading, and understory height at different distances from the center of the stand as well. Center was measure at the trunk. Middle was halfway between the trunk and the edge. Edge was measured just inside the outer limits of the canopy, and outside was measured 1 m outside the canopy.

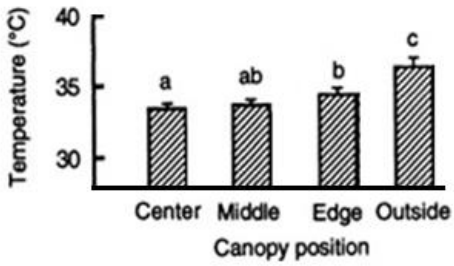



Figure 24. Air temperature at different differences from the center of a stand of live oaks. Different letters indicate a significant difference. Modified from: Gass, L., & Barnes, P. W. (1998). Microclimate and understory structure of live oak (Quercus fusiformis) clusters in central Texas, USA. *The Southwestern Naturalist*, 183-194.

**Analyze the Figure**

- Did distance from the center influence air temperature?
- Do these data support the hypothesis, partially support the hypothesis, or refute the hypothesis? Explain your answer.

Soil temperature was significantly higher than air temperature outside the oak clusters. The least shading was also outside the oak clusters. Understory vegetation height was lower at the edge than the center or middle.

**Evaluate the Hypothesis**

- In what ways did the oak trees influence microclimate?
- Did the microclimate differences result in more growth in the understory?

**Do Try this at Home: Microclimates**

On a sunny day, explore the different temperature of various places. If you have a thermometer with an appropriate range, use it. Otherwise just try to feel the difference with your hand. Is there a difference between the north and south sides of buildings? Can you feel a difference between asphalt and concrete? Is it cooler by a fountain or stream than away from it?

You may also notice differences in wind or humidity.

**Check Your Understanding**

- Describe some factors that can influence microclimates
- In one mountainous area where glaciers have been gradually melting over the years, local people have started to paint the rocks white. Explain why this might help to restore some of the glaciers

**Evolutionary Perspective: Did Climate Variation Drive Human Evolution?**

Humans and chimpanzees share a common ancestor. Fossils show that the two lines split about 6 million years ago (Figure 25, next page). The species in the non-chimpanzee line are called hominins. Some of the species in this line survived for millions of years, then went extinct. One line, which included members of the genus *Homo*, led to modern humans, *Homo sapiens*. What caused the evolution of the traits we have today?

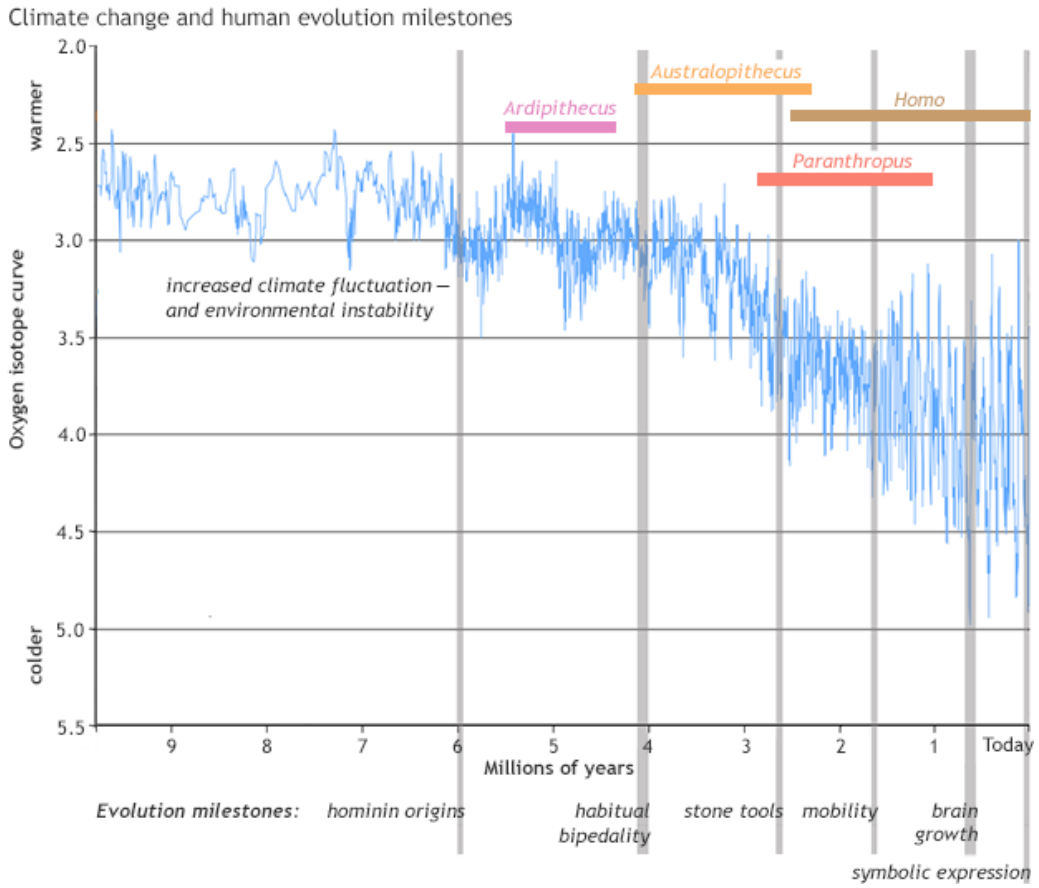
One hypothesis is that past climate change and variation selected for individuals that were more adaptable. Evidence from deep sea cores tells us that the climate was becoming colder, drier, and less predictable when the hominin line split from the chimpanzee line. Two effective responses to change in an area are to adapt or leave.

Individuals that were better at walking upright could probably travel farther to search for places with better climates and more food. These better walkers would have left more offspring than less mobile members of the population.

Brain tissue is expensive for an organism to make and support, so smaller brains can be an advantage when the environment stays the same. New and variable environments would have produced new challenges that required the ability to solve new problems, make plans, and recognize whether the new plans work. The more the environment varied, the more it would have favored hominins that had larger brains that allowed them to change their behaviors. Larger brains would account for the ability to make and use stone tools and develop culture.

**Continued**

**Evolutionary Perspective: Did Climate Variation Drive Human Evolution? cont.**




https://www.climate.gov/media/13341

Figure 25. Change in climate and changes in the ancestors of humans. The colored bars show the time periods with fossil evidence of species from that genus. For example, the first fossils from the genus *Homo* appear to be a bit less than 3 million years old. The vertical gray bars shows periods when evolution milestones occurred:

- Hominin origins: Split between human and chimp lines
- Habitual bipedality: Upright walking evolved
- Stone tools: Evidence of making tools from rocks appears
- Mobility: Ability to travel efficiently over long distances evolved
- Brain growth: Brain size increased rapidly
- Symbolic expression: Oldest cultural evidence (e.g. paintings and art)

# Key Concepts

- Climate is a long-term view of weather.
- Angle of sunlight causes seasonal differences in daylength and temperature.
- Heat can be transferred or stored, especially by water.
- Latitude and elevation are major influences on climate.
- Proximity to water influences temperature and precipitation.
- Aspect, color, shading, and evaporation influence microclimate.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately describe and explain the influence of latitude and altitude on temperature*
2. *Explain how heat movement and storage influence weather and climate*
3. *Analyze how temperature and geography influence precipitation*
4. *Provide valid predictions for how aspect, color, shading, & evaporation will influence microclimate*

1. Imagine that you are in a city near the Great Lakes around 45 $^{o}$N latitude in winter.

    A. The weather forecast says that it will be warmer near the lake and colder farther inland. Explain why this is.
    *(Learning Outcomes 1 & 2)*

    B. There is a wind chill warning in effect. You friend says she will make sure she leaves her car in a garage overnight so that it will be more likely to start in the morning. Assume that the garage is not heated. Is she correct about how wind will influence the temperature of the car? Explain your answer. *(Learning Outcome 2)*

    C. The forecaster predicts that wind over the great lakes will cause heavy snowfalls in some areas. If the wind is blowing from east to west, which side of the lake will receive more snow? Explain your answer. *(Learning Outcomes 2 & 3)*

2. Figure 26 is a climate graph for a city with an average annual temperature of 9.8 $^{o}$C and an annual precipitation of 1253.2 mm. It is 59 m above sea level.

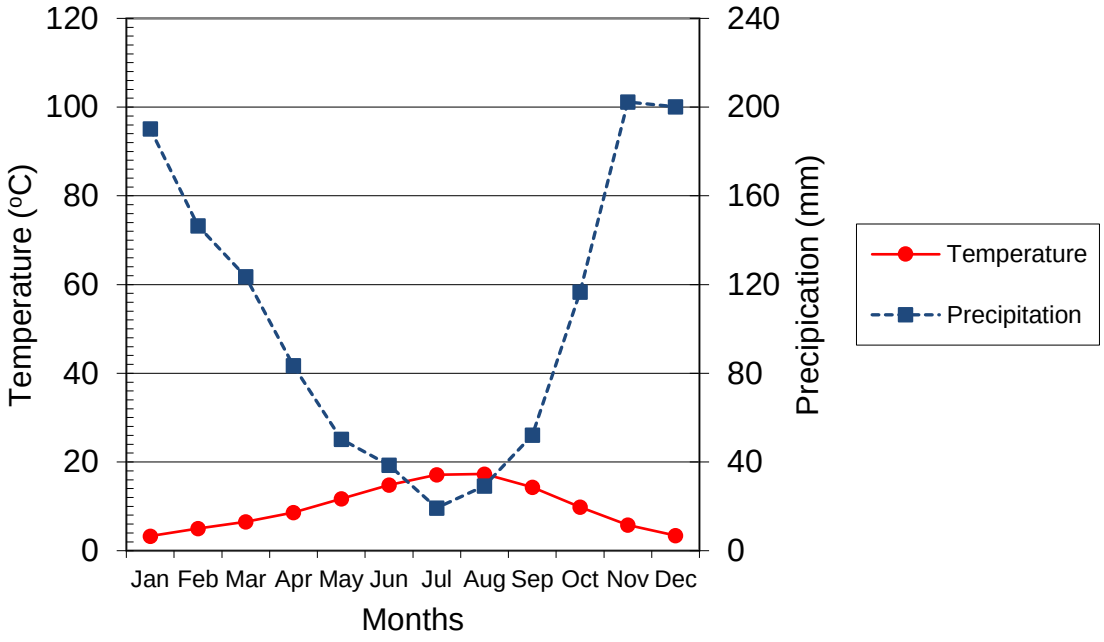



Figure 26. Climate graph.

A. What can you observe about the city described by this graph? What are the minimum and maximum average temperatures? When do they occur? Is this location seasonal? Is there a dry season?

B. What can you infer about this city? Do you predict that it receives a lot of snow? Would you expect fire to be a major danger? Is it in the Northern Hemisphere, the Southern Hemisphere, or on the equator? Is the growing season long or short?

C. If there were a mountain near this city, what would you predict about its temperature and precipitation? Explain your reasoning. *(Learning Outcomes 1 & 3)*

3. If you were growing vegetables in a community garden, how might microclimates influence the best placement of plants? *(Learning Outcome 4)*

4. Why is there very little snowfall at the poles? *(Learning Outcomes 2 & 3)*

**Unit II: The Non-living World**

# Chapter 7: Soil, Foundation of Life on Land

### Case Study Part 1: The Jack Pine Mystery

**A**

https://www.usgs.gov/media/images/snowy-mountain-adirondack-park-ny

**B**

http://commons.wikimedia.org/wiki/File:Jack_Pine_Barren.jpg

Figure 1. **A**. Typical Adirondack forest. **B**. Jack pine (*Pinus banksiana*) barren in New York State, USA.

**Analyze the Figure**

- Which area has more open space?
- Describe any differences you see between the trees.

Tucked into the vast northern hardwood and mixed hardwood-conifer forests of New York State are patches of jack pine "barrens." Jack pine trees are usually found farther north and should be crowded out by the hardwoods and other pine species this far south. So what are they doing so far from their normal range, surrounded by trees that "belong" there?

The root of the mystery lies in the soil. The soil in the main part of the forest has a moderately high level of moisture and nutrients. It is fairly deep. Under the jack pines the soil layer is very thin, only about 20 cm deep. It is acidic, low in nutrients, and rather sandy. Just under the soil is a layer of flat sandstone. When water flows through the soil, it hits the bedrock and drains away, leaving the soil dry. The trees in the surrounding forest do not do well in this soil. The jack pine thrives on it.

Where does soil come from and where does it go? What makes it different in different places? This chapter will discuss these questions and the essential role of soil in terrestrial ecosystems.

**Learning from the Case Study**

- Why do the jack pines seem out of place?
- How is the soil in the jack pine barrens different from the surrounding soil?

# Learning Outcomes

1. *Accurately describe the composition of soil and why it varies under different conditions*
2. *Explain how soil is formed and how it is moved by erosion and deposition*
3. *Describe the importance of soil to the ecosystem*
4. *Accurately explain the development of soil horizons*
5. *Explain why soil nutrients and pH vary and why this is important*

**Vocabulary Toolkit**

**Word Watch List**

**Weathering**: The breakdown of rock due to exposure to factors such as precipitation and wind
**Humus**: Organic material that is completely broken down
**Erosion**: Movement of soil due to water or wind
**Deposition**: Process of soil settling in a new area after being moved by erosion
**Infiltration**: Process of water sinking to deeper layers in the soil
**Runoff**: Water that flows across the surface of the soil
**Soil horizon**: Layer of soil with a distinctive color and texture
**Leaching**: Removal of nutrients from soil due to water flowing down through it
**Cation Exchange Capcity (CEC)**: Ability of soil to retain positively charged ions
**Micronutrients**: Nutrients that plants need in small amounts

## Soil Is a Mixture of Materials

Soil is essential to life on land. While it is possible to grow plants without soil in artificial setups, natural growth of plants depends on soil. Different plant species require different amounts and types of soil.

Soil is made of minerals, organic matter, water, and air (Figure 2). The mineral part of soil is tiny particles of what used to be rocks. The organic part is made of dead material and waste products from living organisms. Soil also contains water and air in different amounts. For example, soil can be compacted when animals walk on it. Compaction pushes some of the air out of the soil. Air can be added to soil by the action of animals or roots in the soil. Farmers break up compacted soil by plowing it. Water content in the soil will depend on how much precipitation and evaporation an area gets. This will be discussed in more detail in Chapter 8.

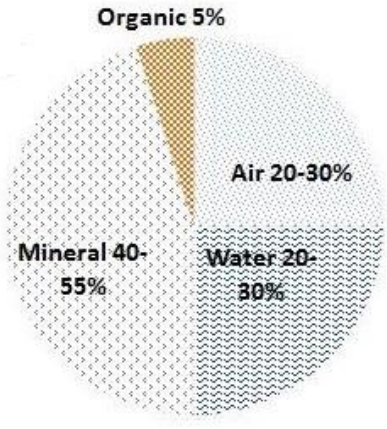



Figure 2. An example of the composition of soil. Actual proportions vary widely.

**Model Skill: Pie Charts**

Pie charts show how much of each component makes up a whole. If the value of each category in the pie chart is converted to percentages, the total must be 100% (though there may be a bit more or less due to rounding). Pie charts illustrate *proportion*, not *quantity*. For example, Figure 1 shows that any given soil sample might be 20-30% water.

In Figure 1, organic material made up 5% of the soil. The organic material is also made up of various components. Table 1 provides an example of how the organic material may be divided between these components.

Table 1. Composition of the organic material in a hypothetical soil sample.

| **Component** | Living Organisms | Fresh Waste (leaves, feces, carcasses, etc.) | Actively Decomposing Waste | Humus |
|---|---|---|---|---|
| **Percent** | 5 | 10 | 45 | 40 |

To make a pie chart, start with percentages that sum toapproximately 100%. There are 360 degrees in a circle. If living organisms make up 5% of the sample, calculate 5% of 360. Multiplying 360 by 0.05 gives you 18. This means that an arc of 18 degrees of your total circle would be the outer edge of your “living organisms” piece of the pie. Fill in a bit less than one “slice” of the pie chart to show 5% of the total pie. Repeat this with each of the other components.

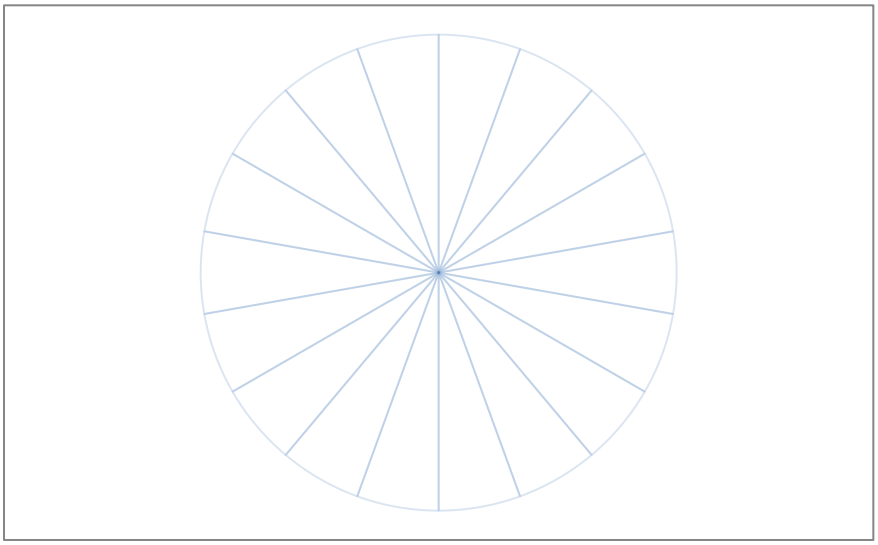


Figure 3. Composition of the organic component of a hypothetical soil sample. The lines divide the circle into arcs of 20 degrees.

You would **not** use a pie chart to show something like how many tons of topsoil were lost to erosion each year for the past decade. For that, you would want to show the quantity of material lost each year. A line chart would be appropriate.

**Misconception Alert: Soil is all the same.**

**FALSE.** Soil varies in many ways. It can be dark brown, moist, and "fluffy" with air. It can be dense, sticky, and orange. It can be gray and dry. Soil type depends on many factors, including environmental conditions, historical events, and the rock that provides its minerals. Each type of soil supports its own populations of microbes, fungi, plants, and animals.

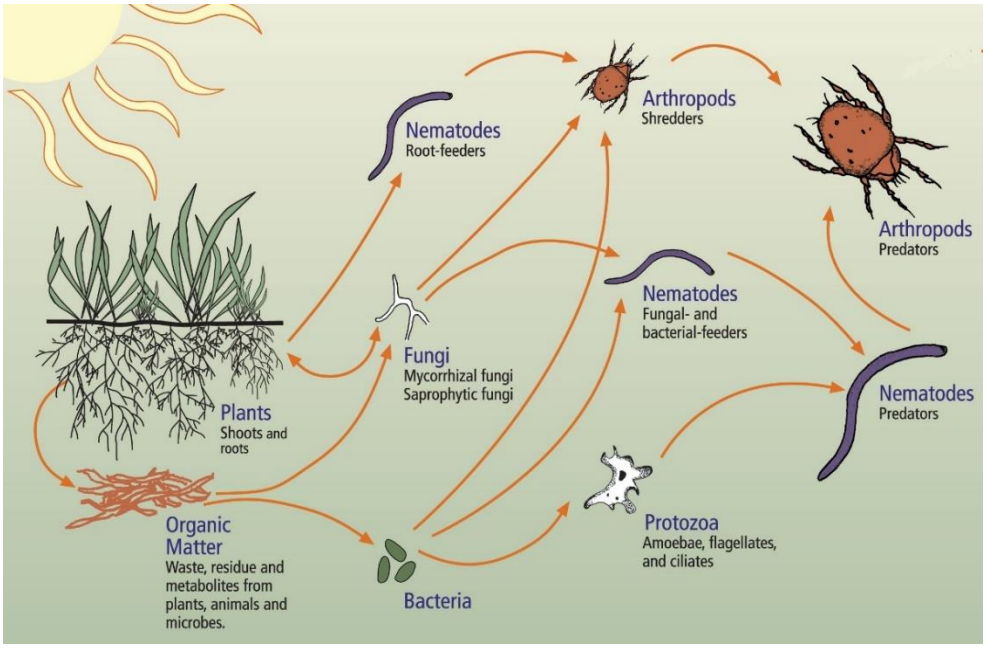
**Check Your Understanding**

- What are the four major components of soil?
- Why might the proportions of the components vary?

**Biotic and Abiotic Factors form Soil**

The mineral part of soil comes from breaking down rocks into small particles. Exposure to water, wind, and similar forces breaks down the rock in a process called **weathering**. If water gets into cracks in the rocks and freezes, it will expand (see Chapter 3), possibly cracking the rock and allowing more water to enter. Roots may force their way into cracks in rock. The breakdown of rock is usually a very slow process. Rocks can be broken down by physically hitting each other, or by major forces such as earthquakes. Different types of rock form soil with different properties.

The organic part of soil comes from the breakdown of material that once belonged to living organisms. It includes fallen leaves, dead animals, feces, and similar material. Soil is full of living things, including microbes, animals, the roots of plants and the root-like extensions of fungi (Figure 4). As living things die above or below the ground, decomposers such as insects, worms, fungi, and microbes break them down. Some organisms, such as earthworms, bring dead material from the surface down into the soil. When the organic material has broken down until the particles are not visually identifiable, it is called **humus.**




Adapted from: http://www.nrcs.usda.gov/wps/portal/nrcs/photogallery/soils/health/biology/gallery/

Figure 4. Some of the organisms that live in soil.

Soil formation is very slow. Under the best possible conditions, only about 1 mm of soil can be produced per year per surface unit. This is the thickness of a dime. Conditions that are good for plant growth tend to be good for soil formation since plants are a major source of organic material. Good conditions for decomposers are also important because they will be processing the material into humus. Decomposers usually do well in warm, wet soil that is not too acidic. Both production and breakdown will be slow in colder, drier conditions. When water is frozen, these processes slow down drastically. In poor conditions, it may take a thousand years to make 1 mm of soil. In extremely dry areas, it may never form at all.

**Do Try this at Home: Decomposition**

What conditions are best for the breakdown of organic material? Take squares of mesh-like material from a fabric store and place material such as leaves in the middle of each. Use the same amount and type for each square. Gather up the corner of each square and tie the top with string. Leave a long “tail” of string at the end. Weigh the bags and record the weights. Then bury the bags in different locations, leaving the “tail” of string attached to a rock or stake. After a week or more (the timing depends on where you live) dig them up, let them dry, and measure the weight again. The lightest bags have had the most decomposition. You can experiment with different factors to explore what influences decomposition rate.

**Case Study Part 2: Why Isn't There More Soil in the Barrens?**

Geologists have learned that massive floods about 13,000 years ago removed the soil from the land that would become jack pine barrens. The floods left bare sandstone behind. Soil forms very slowly, but a long time has passed. How much soil would we expect? In the best conditions, about 1 mm of soil will be created each year.

1 mm of soil/year X 13,000 years X 1 cm/10 mm = 1300 cm of soil

So why is the soil layer only around 20 cm deep? One answer is that the conditions were not good for soil formation, particularly in the early years. When there is already soil around, plants can grow, providing habitat and resources for the organism that decompose organic material. Soil does not form quickly on bare rock because there's almost no organic material to break down and not much to support worms, soil bacteria, or other soil-making organisms.
Another limit on the rate of soil-making is the length of the growing season. The American Northeast has cold winters that last for months. During the winter months, there is almost no plant growth or breakdown. How did the area get covered with even a shallow layer of soil? Part 3 of the case study will explore this.

**Learning from the Case Study**

- Why is soil formation so slow when it starts on bare rock?
- Why might the climate of the Adirondack region result in slower soil formation?
- Could soil have been brought to the area by natural forces? Explain how that might happen.

**Check Your Understanding**

- What is the source of the mineral part of soil?
- What is the source of the organic part of soil?
- How will climate influence how fast soil forms?

**Erosion Moves Soil**

The soil found in a particular place may not have formed there. Soil is moved from place to place by wind, water, and glacier movement. These are forms of **erosion** (Figure 5). Humans and other animals may also move soil. As we know from the first law of thermodynamics, the soil cannot just disappear. It travels to another place and is deposited when the air or water slows down. This process is called **deposition**.

http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/landuse/crops/erosion/

Figure 5. Soil can be eroded by water or wind.

**Analyze the Figure**

- What land use practices do you see that might be causing the erosion?
- Where might this soil end up?

The speed of the moving air or water determines whether objects, such as a tiny speck of dust or a giant boulder, will be moved. Faster moving fluids pick up and carry heavier objects. As we know from the second law of thermodynamics, energy is lost as it changes from one form to another. As the wind or water moves, friction will slow it down, unless more energy is added. As the fluid slows, the largest objects will fall out first. Soil in water may be carried all the way to the ocean, or it may be deposited on banks or river bottoms. Soil in the air can travel thousands of kilometers before falling to the ground.

Erosion is a particular problem where vegetation has died, burned, or been removed in other ways. Plants help to hold soil together, and leaf litter protects the soil from wind. Under wet conditions, water washes soil away, but under dry conditions, wind blows it away. A variety of farming practices are used to try to control the loss of soil, but the United States loses soil faster than new soil can be created. Erosion is a major concern because the loss of fertile topsoil means a loss in agricultural productivity. Airborne soil can be hazardous to human health (see **Make the Medical Connection: Erosion and Respiratory Health**).

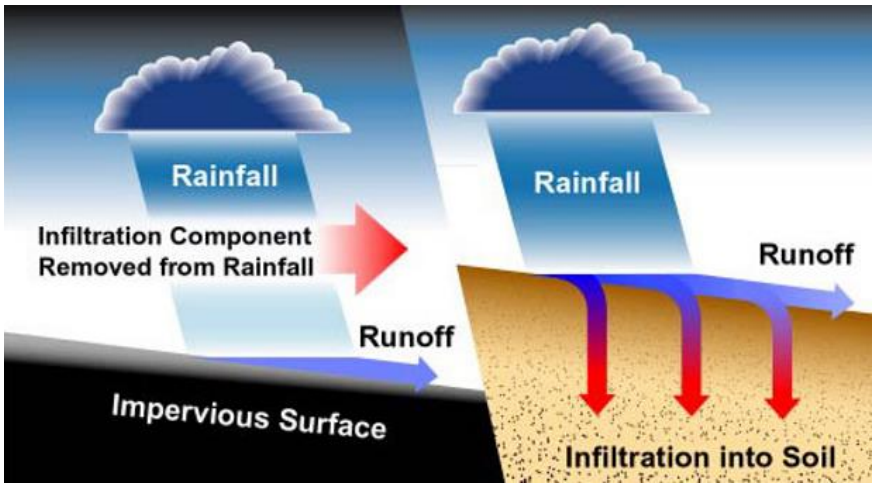
**Make the Medical Connection: Erosion and Respiratory Health**

http://www.epa.gov/region9/mediacenter/phoenix/images/duststorm.jpg

Figure 6. Sandstorm in Phoenix, AZ, USA in November of 2009.

Sandstorms are a natural occurrence in some parts of the world. However, in some areas these problems are increasing. The topsoil blows away, and moisture cannot be stored in soil or plant material. These storms are not just an inconvenience; the poor air quality is a major health concern, causing deaths from asthma and other respiratory issues.

Because erosion increases with the amount and speed of flowing water, it is important to understand what can happen to precipitation or snowmelt when it reaches the soil. The water may soak into the soil or remain on the surface. **Infiltration** is the process of water sinking to deeper layers in the soil. If the water arrives on the surface faster than the surface can absorb it, it becomes **runoff**. Heavier rainfall, steeper slopes, and soil that is difficult to infiltrate will cause more of the water to become runoff (Figure 7). High levels of runoff cause erosion and flooding. Major erosion events can be hazardous (see **Why It Matters: Landslides**).




Modified from: https://www.tucson.ars.ag.gov/kineros/home.html

Figure 7. If the precipitation rate is higher than the infiltration rate, the excess water becomes runoff. If the precipitation rate is lower than the infiltration rate, water will be absorbed by the soil. Different types of soil and other surfaces have different infiltration rates. Impervious surfaces prevent all infiltration.

**Why It Matters: Landslides**

http://pubs.usgs.gov/of/1994/ofr-94-0615/fig_2.jpg

Figure 8. Tully Valley landslide in New York, USA. Notice the original boundaries of the fields and the large portion now missing.

Landslides are major erosion events that occur when the forces pulling soil downhill are greater than the forces holding it in place. This could happen on any slope, but several variables make landslide more common. Steeper slopes will be more likely to slide. Vegetation helps to hold soil together. When it is removed, erosion increases. Water saturating the soil will also weaken the attachment of soil particles to each other, so flooding and landslides often occur together. Earthquakes and tremors can also cause landslides. Hundreds of people were killed in 2009 in Sumatra when earthquakes caused a massive landslide.

Why would people choose to live and build in slide-prone areas? It could be because safer areas have already been used, but there is still pressure for more development. In some areas, houses or offices on cliffs or mountainsides are valued for their views or prominence on the landscape.

- Should governments prevent people from building in slide-prone areas, or should citizens be allowed to weigh the risks themselves?
- Should people living in high-risk slide zones be encouraged or forced to move? If so, who should pay the cost of resettling them?

The size of the mineral particles in the soil influences whether water stays on the surface or infiltrates it (Figure 9). The largest mineral soil particles are sand. Silt is smaller, and clay is smaller than that. The proportions of these particles determine the classification of soil (see

**Taking It Further: The Soil Texture Triangle**). Precipitation may also fall on other surfaces that might be impermeable to water (such as pavement) or highly permeable (such as gravel).

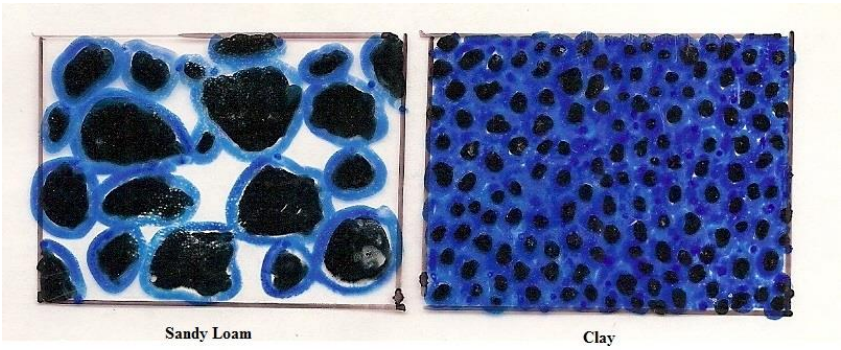



Figure 9. **A**. Sandy loam is made of comparatively large particles (black) of varying size and shape. This allows for larger air spaces (white), even when each particle is coated with water (blue). **B**. Clay particles are very small and fairly uniform. Little air space remains between particles, especially when each particle is coated with water. Additional water is prevented from entering the soil.

When water falls on high-clay soil, it soon fills the limited spaces between particles, making wet clay sticky and dense. Water pools on the surface (Figure 10A) or flows downhill as runoff. Pooled water may evaporate before it has a chance to seep into the soil. The high-clay soil shrinks as it dries. This can result in large cracks (Figure 10B).

**A**

https://upload.wikimedia.org/wikipedia/commons/6/66/Former_East_Golds_clay_quarry_-_geograph.org.uk_-_1736511.jpg

**B**

https://www.climatehubs.usda.gov/hubs/Southwest/recent-additions?page=1

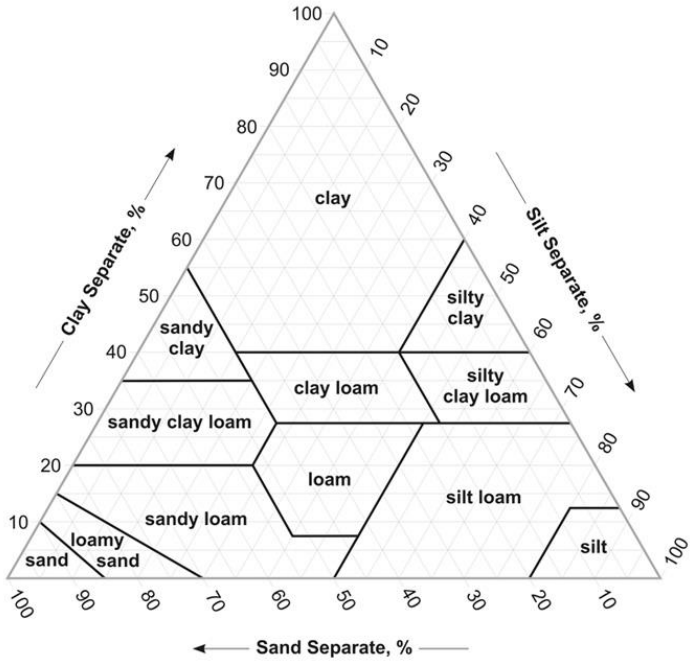
Figure 10. **A**. Soil with high clay content keeps water from draining, so water pools on the surface. **B**. When it dries, cracks form in the high-clay soil.

When particles are larger and less regular in shape, there is more air space between them. This makes the soil easier to work with farming implements and makes it easier for water and

organisms to penetrate the soil. Sandy soil has so much air space that water tends to run through it rapidly, before organisms can use it.

**Taking It Further: The Soil Texture Triangle**

The USDA soil texture triangle is used to categorize soil based on the proportion of sand, silt, and clay (Figure 11). Sand can be up to 1mm in diameter. Silt is 2--50 μm and clay is any mineral particle smaller than that. A micron is one millionth of a meter. Any mineral pieces larger than sand are considered gravel and are not used in this classification.




http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167

Figure 11. US Department of Agriculture soil texture triangle.

If a soil is 60% sand, you would start by finding 60% on the sand axis. If it were 15 % clay, you would find where the 15% line from the clay axis met the 60% line from the sand axis. You would not need to use the silt axis because the three proportions will add up to 100% and you already know two of them. You could use the axes in any order to get the same result. In this case, your soil is sandy loam, and good agricultural soil. Classify a soil that is 50% sand, 35% clay, and 70% silt.

**Case Study Part 3. How Did Soil Get to the Barrens?**

Huge floods 13,000 years ago swept soil far downstream of the future site of the jack pine barrens. Soil is always moving. After erosion scraped the sandstone nearly bare, wind and water carried soil from other areas to the sandstone. This soil acted as a sort of soil "start-up" investment. The deposited soil allowed plants and soil organisms to start invading the area. The new food sources and habitat could have attracted other organisms. Wastes and dead material from these organisms could have been broken down by decomposers, making more soil. Large areas of the sandstone have been covered by soil and vegetation, but bare rock remains as well. (See photos and learn more at https://www.adirondackexplorer.org/stories/northern-adirondacks-gulf.)

**Learning from the Case Study**

- How would deposited soil make soil formation happen faster?
- What might change the amount or rate of deposition?

**Check Your Understanding**

- How can soil be removed from a place by erosion?
- What would cause deposition of soil?
- How does particle size influence the movement of particles, water, and nutrients?

**Climate Influences Soil Dynamics**

As discussed earlier, temperature, wind, and moisture influence how soil forms, changes, and moves. Microbes that break down organic material are more active in warm, moist conditions. They tend to be less active in cold, dry, or acidic soil. There is little vegetation to break down into humus if the growing season is short, or if there is not enough water for plant growth. High precipitation levels make soil acidic and leach out nutrients.

If you were to dig a hole in the soil in your area, you would see bands of soil—called **horizons**—that might be very different in their color and texture. The color can tell a lot about the soil. Soil high in organic material is usually dark brown to black. As water flows down through the soil, it can dissolve clay and nutrients and carry them further down into the soil. This process is called **leaching**. Picture hot water moving through a layer of coffee grounds, carrying the chemicals that will make a cup of coffee. This is a leaching process. Soil that has been leached of organic material is usually red or orange due to the color of iron that is left behind. Calcium carbonate, salts, sand, and ashes from past fires and volcanoes can leave gray or white bands. Other colors result from different minerals and influences in the environment. Soil horizons vary a lot between locations due to differences in climate, the type and location of minerals in the area, major disturbances, slope, land use by humans, and other factors.

Ecologists use a classification system to describe and organize the variation among soils. The main bands of the soil horizons are usually classified as the O (organic) horizon on top, with horizons A, B, and C underneath (Figure 12).

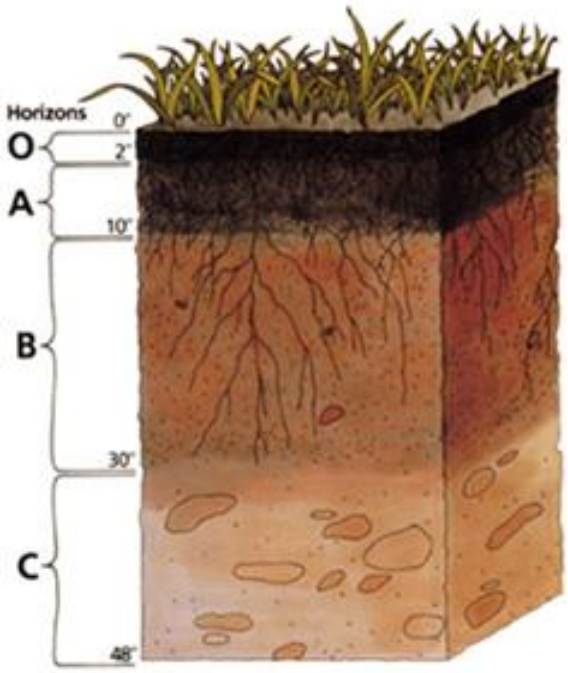
**Key to the Soil Horizons:**

O: The organic horizon made of humus (decomposing organic matter)

A: Zone where shallow roots, microbes, and invertebrates are common. Often called the zone of leaching because water carries nutrients out of this zone into the B horizon. (In some systems, the lighter, lower part of this horizon is called the E horizon)

B: Zone where deep roots are common. Often called the zone of deposition because nutrients leached from the A zone are deposited here. The depth is determined by how much water the soil receives at one time.

C: Zone containing rocks that are being broken down. Comparatively little life or organic material.




http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/kthru6/?cid=nrcs142p2_054308

Figure 12. An example of a soil profile. The depth and color of each layer depends greatly on climate and other factors. Some systems divide zone A, calling the topsoil the A horizon and the leached zone below the topsoil the E horizon.

The organic, or O, horizon is made of decomposing organic material. The leaf litter on top of the soil is not considered a part of the O layer. Decomposers such as earthworms, insects, and microbes are constantly breaking down leaf litter into humus. The depth of the O layer depends on both the supply and breakdown of organic material. In dry and cold climates, there may be a thick layer of plant material above the O layer that has not yet broken down. Acidic materials, such as evergreen needles, are very acidic and are also slow to break down.

The A horizon is the uppermost layer that looks like dirt. It contains minerals as well as decomposing material. It has a lot of living organisms, such as animals, microbes, shallow roots, and the root-like structures of fungi. The activity of these organisms helps to mix decomposing organic material into the A layer. It receives water from precipitation, and sometimes snow melt or flowing water. As materials break down in the O horizon, they will be drawn into the A horizon

by the movement of water and the activity of organisms in the soil. Areas that stay warm and wet enough for plant growth and decomposer activity can have thick topsoil layers. Areas that are too dry and either too hot or too cold may have little or no topsoil (Figure 13).

**A**

https://en.wikipedia.org/wiki/Aridisol#/media/File:Aridisol_profile.jpg

**B**

https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/gelisols

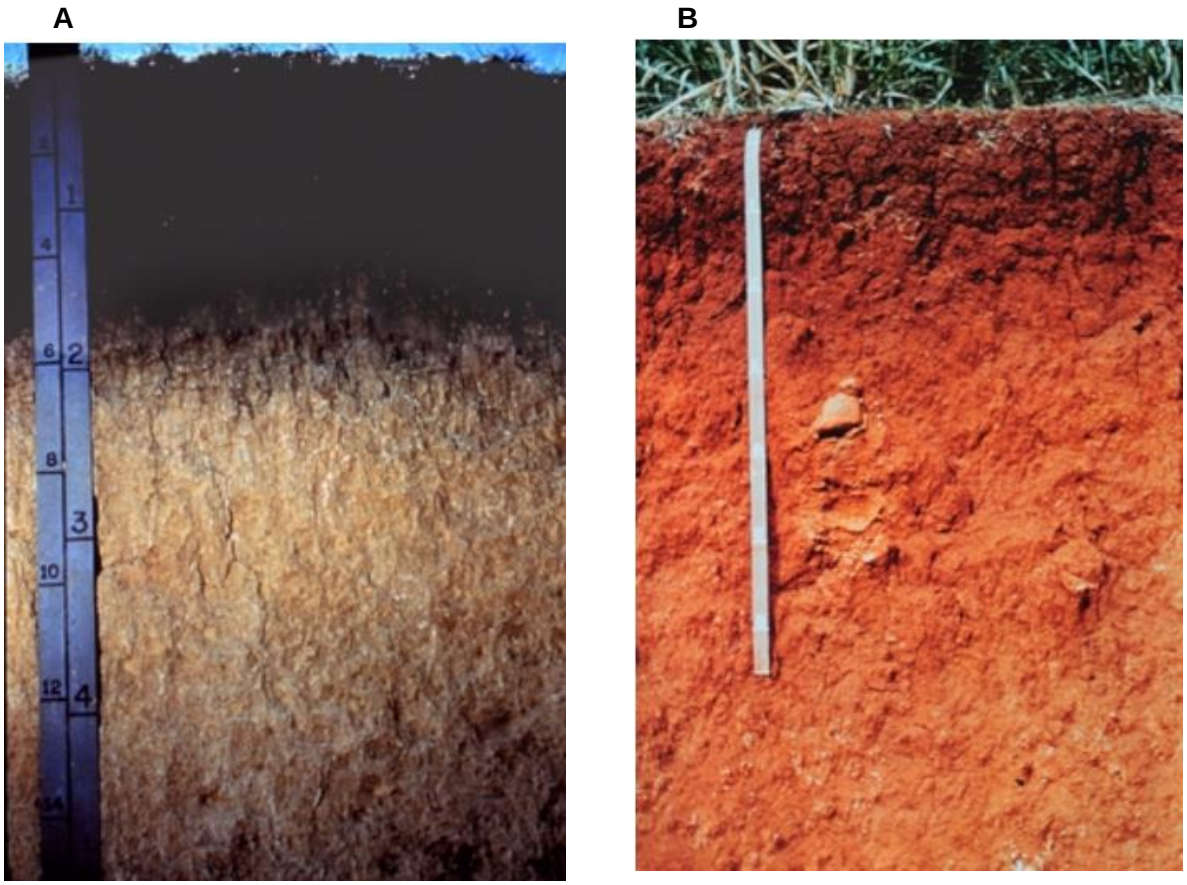
Figure 13. Soils that are too hot (**A**), cold (**B**), and dry (both) have little or no topsoil because topsoil requires both plant growth and active decomposition. The units on the measuring tape in A are decimeters.

Many of the organisms that break down organic material depend on oxygen. If soils are usually saturated with water, only anaerobic respiration can occur. Some anaerobic bacteria get energy from breaking down ferric iron to soluble, colorless ferrous iron resulting in gray soils with little or no development of horizons (Figure 14)

https://www.fws.gov/story/dirt-soil

Figure 14. Soil from non-wetland (left) and wetland (right) areas, demonstrating how anoxic conditions influence soil. The wetland soil has been stripped of ferric iron by anaerobic bacteria.

If precipitation tends to be moderate and spread out over time, nutrients stay in the A horizon (Figure 15 A). Grasslands tend to have moderate rainfall and are well known for having a thick, dark layer of topsoil. Most former grasslands in the USA have been converted to agricultural use because of their topsoil. Frequent heavy rainfall will carry the dissolved nutrients down below this zone (Figure 15 B). Tropical soils are usually poor in nutrients and orange or red because the nutrients have been leached away.




http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf

Figure 15. Soil profiles showing the result of different precipitation levels. **A**. The grassland soil from Kansas, USA shows a dark A horizon that is rich in organic material. Rainfall is approximately equal to evaporation, so there is little leaching. **B**. The soil from a rainy region of Hawaii, USA is orange because most of the organic material has been leached out, leaving iron and aluminum. In A, the units on the left side of the tape are decimeters. The units on the right are feet.

The B horizon is the subsoil where those leached nutrients and other molecules end up when the water stops moving down through the soil (Figure 16). It is often called the zone of deposition because nutrients are deposited there. It only receives water occasionally, so it tends to be dry. It contains very little organic material.

**A**

Modified from:
http://www.lewiscountysoilandwater.com/education.php

**B**

http://www.djibnet.com/photo/spodosols/ultic-haplorthod-sandy-siliceous-thermic-new-hanover-county-north-carolina-8742044190.html

Figure 16. **A.** Soil horizon from Lewis County, NY, USA. The topsoil in the A horizon is dark. The lighter band below (which is the lower A horizon or E horizon) has probably been leached of iron oxide, which has travelled to the B horizon, making it orange. The rocky gray material at the bottom (C horizon) is mostly rocks left by a glacier about 10,000 years ago. **B**. Soil profile from New Hanover County, NC, USA, a sandy coastal area. The large, irregular sand particles allow water to flow quickly through the soil. The dark topsoil layer is very thin. The zone of leaching is almost white. The dark B layer below shows streaks where nutrients and clay have been deposited. The units marked on the left side of the tape are feet. The units on the right are decimeters.

The C horizon is almost all rocks. It may be broken up, allowing water to travel further down, or it may be an almost solid sheet of rock. This can trap water. If the rock layer is tilted, the water will flow away down the slope.

While the same climate might produce various soil horizons depending on the local minerals, slopes, and historical factors, there are some generalizations that can be made about soil and climate (Figure 17)

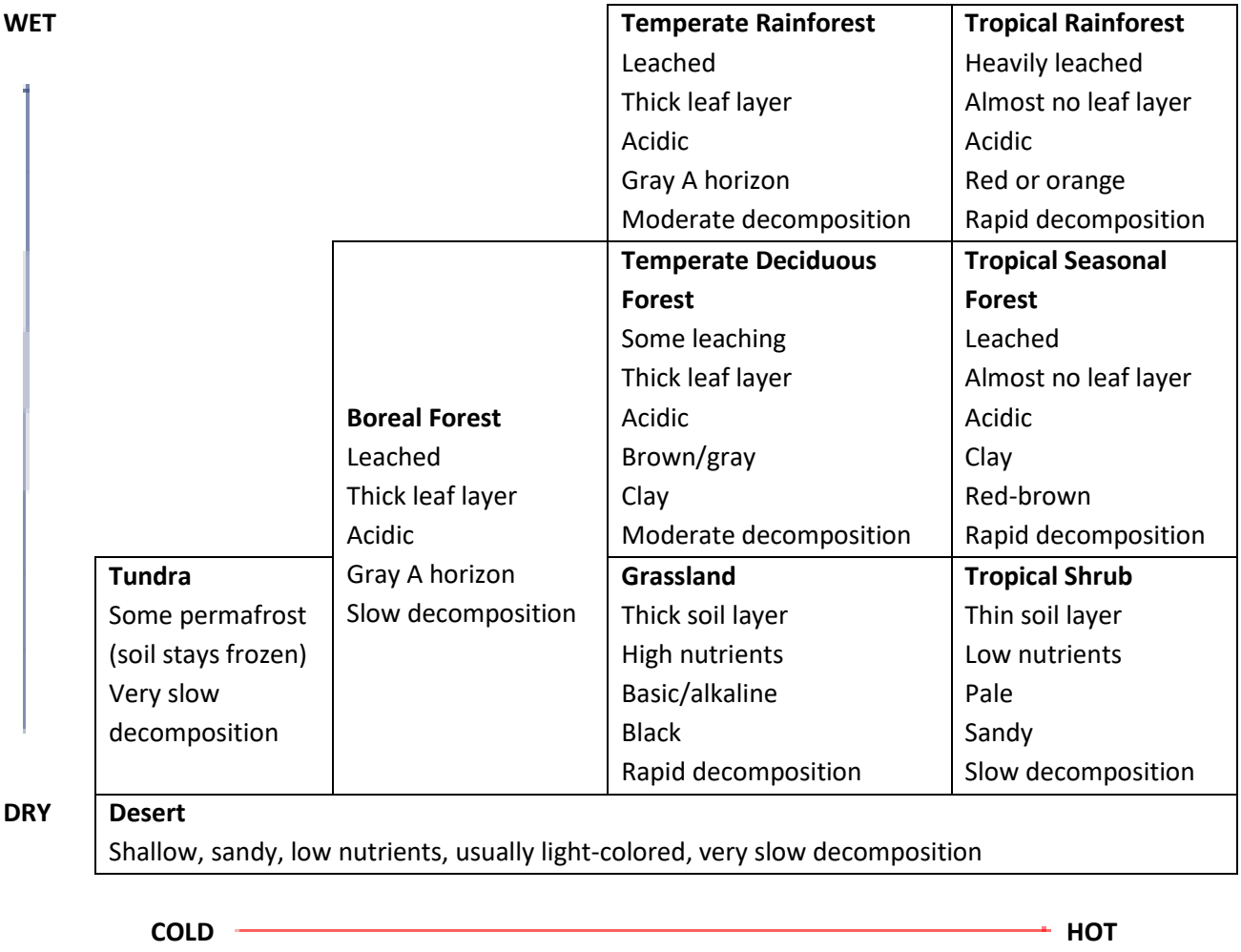



Figure 17. Temperature and precipitation influence soil. Microclimates and other factors will still lead to variation within the same climate zone. The categories of each zone will be discussed more in Chapter 8.

**Analyze the Figure**

- Which biomes have a thick layer of litter or organic debris? How is this related to decomposition?
- Which biomes will produce new soil fastest?

The warm, wet tropical forests produce a lot of dead vegetation that can be broken down quickly by bacteria and other decomposers that thrive in these conditions. It might seem that soils in the tropics would have plenty of nutrients, but the heavy rains also cause heavy leaching of nutrients. As noted earlier, iron oxides remain, giving the soil an orange or red color.

The soil in forests with conifer trees such as pine and spruce tends to be gray. The acid from the conifers and the cooler temperatures slow the bacterial decomposition of organic material

into humus. Leaching can remove nutrients from the soil, but high precipitation can also dilute the acid.

Tundra and desert areas have very little plant growth, so there is little organic waste. The conditions are not good for decomposition either, resulting in thin, poor soil. In the tundra, the soil may not thaw completely, leaving a layer of permafrost—soil that does not thaw—below the surface that roots and water cannot enter.

In grasslands, precipitation is approximately equal to evaporation. Nutrients are not leached out of the soil. There is usually a lot of plant growth, and the part of the grasses that are above ground break down to add nutrients. Decomposition is rapid when it is warm and there is sufficient moisture. A dark, nutrient-rich, alkaline soil forms in grassland biomes.

These are all generalizations about how average annual precipitation and temperature will influence soil. Other factors can be important too. Does all the water arrive at once, causing leaching and erosion, or is it spread out? Is the land flat or do steep slopes allow runoff? What is the rock like? Is the climate seasonal, or the same all year? How does the activity of animals influence the soil?

**Check Your Understanding**

- What does color tell you about the soil horizon?
- What factors create different soil horizons?
- How does climate influence the horizons?

### Soil pH Influences Soil Nutrients

Recall from Chapter 5 that plants take up nutrients such as nitrogen and phosphorus through their roots. There are also many micronutrients that are needed by plants in much smaller amounts. Different plants have different tolerances for high and low nutrient levels. Human health can also be influenced by the soil in which crops are grown (see **Make the Medical Connection: Soil Micronutrients and Human Nutrition**).

Nutrient content in the soil is increased when organic materials break down or when nitrogen-fixing bacteria add available nitrogen (see Chapter 5). Nutrient content decreases when nutrients are taken up by organisms, leached down the soil column, or washed away by surface erosion.

Precipitation tends to be acidic, so areas with heavy rain and snowfall have more acidic soil. Many important soil nutrients are acidic, so they are retained better by basic soil than acidic soil (opposite charges attract). Clay is good at helping retain these nutrients (Figure 18). Silt tends to hold organic material and non-polar nutrients. The ability of soil to retain these ions is called **cation exchange capacity (CEC)**. Generally, soils with a higher CEC are better for agriculture.

For more on this topic, see **Hypothesis Testing: Can Traditional Soil Enrichment Practices Increase Sustainability?**

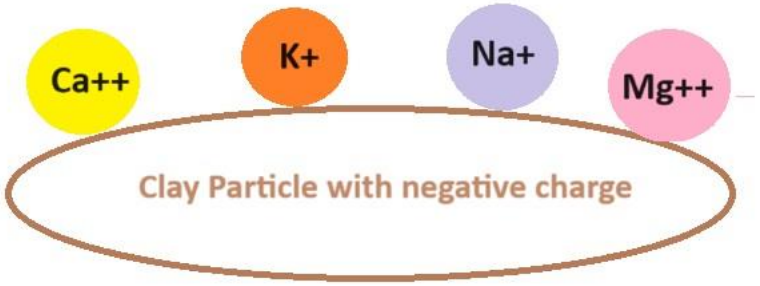



Figure 18. Positively charged nutrients are attracted to a negatively charged clay particle.

**Make the Medical Connection: Soil Micronutrients and Human Nutrition**

When soils lack micronutrients such as iron, the crops grown in these also lack them. The World Health Organization estimates that 2 billion people may suffer from anemia because the iron needed to make hemoglobin is missing from their diets. This causes a low red blood cell count and a lack of oxygen, causing people to be constantly tired and weak, among other health problems. Fertilizers containing micronutrients such as iron, zinc, and iodine can solve this problem, but those suffering from malnutrition can rarely afford to enrich their soil.

Various species of parrots in South America regularly travel to “clay-licks” after they feed (Figure 19). The clay contains a substance called kaolin that has a negative charge. It binds to the positively charged poisonous plant alkaloids in the seeds and unripe fruit that the parrots eat.

http://en.wikipedia.org/wiki/Macaw#/media/File:Parrots_at_a_clay_lick_-Tambopata_National_Reserve,_Peru-8c.jpg

Figure 19. Birds at a “clay lick” in Peru may be protecting themselves from plant toxins by using the ability of clay to bind to positively-charged plant toxins.

Most plants grow better in slightly basic soil, but there are also plants that need acidic soil. Conifer trees such as pines and firs do well in acidic soil. They keep positively charged ions in their needles, so when the needles fall, the soil below becomes acidic. You may have noticed that grass does not grow well under conifer trees.

No one type of soil is best for all organisms. Desert plants are adapted to dry, sandy soil and their roots may rot in soil that holds water. Tropical rainforest plants are adapted to the wet clay found in their habitats and would not do well in sandy soil. Some bacteria thrive in acidic environments, while others die. Some plants thrive in areas that are toxic to other plants (See **Evolutionary Perspective: Serpentine Soils and Plant Communities**).

**Hypothesis Testing: Can Traditional Soil Enrichment Practices Increase Sustainability?**

https://www.fs.usda.gov/features/promise-biochar-forests-grasslands-and-farms-0

Figure 20. Charred wood, or biochar, one of the materials that can be used to enrich soil.

Modern soil science has been critical in increasing crop yields and maintaining soil quality, but some communities have been practicing effective methods of maintaining and improving soil for generations. Soils in Western Africa are not well-suited to agriculture. The region has high precipitation and is warm to hot. As Figure 12 shows, these conditions generally result in soils that are red or orange. Decomposition is fast, but nutrients are quickly carried away by surface water or leached deep into the soil. Soil tends to be acidic, meaning that it has a low CEC. Crop yields are usually very low.

Some people in western Africa and Amazonia have long used soil enrichment techniques that may not only increase crop yields, but also help trap carbon in soil. Farmers add animal wastes, and plant wastes—including ashes and charred wood—to soil. The organic material can provide nutrients. Ashes are effective at buffering soil acidity, raising soil pH and potentially increasing the CEC.

Solomon et al. (2016) compared these enriched African Dark Earths (AfDE) soils with Adjacent Soils (AS) in Liberia and Ghana. They wondered whether the local soil management strategies could contribute to local sustainable agriculture and whether it could be used on a larger scale to decrease greenhouse gas levels.

Hypothesis: Traditional soil management techniques can increase sustainability of agriculture in Africa.

Several variables might contribute to sustainability. Fertile soil can support more people on a smaller area, reducing the need for transforming natural land into farmland. Practices that

prevent erosion, improve air and water quality, and also reduce the need for creating new farms as the old ones become unusable. Carbon sequestration could potentially reduce greenhouse gas levels. Finally, food security tends to reduce social instability and conflict. Stable societies are more able to manage their resources efficiently.

The researchers examined physical and chemical properties of the soil. They used soil horizon measurements to compare the structure of the soil horizons. In untreated areas, soil was yellowish-red all the way down to the parent material, but in areas where people had been treating the soil, the upper 1.8 meters were gray. (See photos and learn more at: https://pure.au.dk/ws/portalfiles/portal/98708238/Solomon2016_AfricanDarkEarths_FrontEnvironmentEcol.pdf).

Soil improvement takes a long time. Interviews with local people indicated that caring for the soil was an important part of the local culture and that the soil enrichment efforts had been going on for several generations. Soil testing supported the statements in the interviews. Carbon dating of the charred wood found in the AfDE soil indicated that the enrichment practice had been going on for 115 to 692 years.

The AS was very acidic, with a pH of 4.3-5.3, as would be expected in this environment. The AfDE was less acidic with a pH range of 5.6-6.4. CEC was tested at different soil depths (Figure 21).

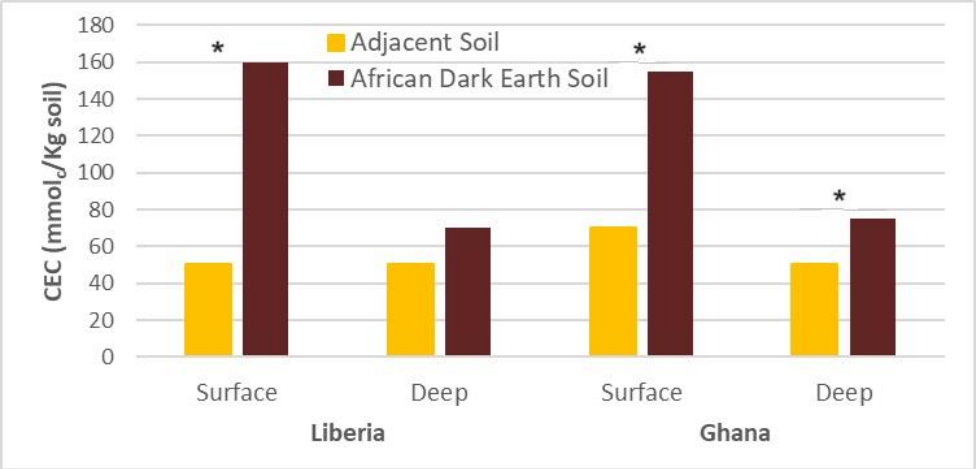



Figure 21. Cation exchange capacity (CEC) near the surface and deeper (over 1 m) in Adjacent Soil (yellow) and African Dark Earth (brown) soils in Liberia and Ghana. Asterisks denote significant differences. Based on: Solomon, D., Lehmann, J., Fraser, J.A., Leach, M., Amanor, K., Frausin, V., Kristiansen, S.M., Millimouno, D. and Fairhead, J.. (2016). Indigenous African soil enrichment as a climate-smart sustainable agriculture alternative. *Frontiers in Ecology and the Environment*, *14*(2), 71-76.

**Analyze the Figure**

- Which soil type had a greater CEC near the surface?
- Why might the difference between soil types be less in the lower part of the soil horizon?

As might be expected due to the higher CEC in the AfDE soils, levels of phosphorus and nitrogen were significantly higher in the AfDE soil than the AS. Total organic carbon was about 2-3 times higher in the AfDE soils. A particular form of carbon that tends to last a long time in the soil was 2-26 times higher in AfDE soil. These findings indicated that, if practiced on a large scale, enriched soil could help to keep more carbon out of the atmosphere.

The AfDE soils are an important source of food crops for consumption and sale, even though they account for a small fraction of the total available soil. The improved soil allows the farmers to grow a greater variety of crops because some plants do not tolerate the untreated local soil.

**Evaluate the Hypothesis**

- Do the data support the hypothesis that traditional soil management techniques can increase sustainability of agriculture in Africa?
- What data are most important in evaluating the hypothesis?
- What other data might be helpful in evaluating the hypothesis?

**Evolutionary Perspective: Serpentine Soils and Plant Communities**

Burton, 1997

Figure 22. Serpentine outcrops (rocky areas) in Santa Barbara Co., CA, USA.

Serpentine soils have high levels of some toxic heavy metals (such as nickel and chromium) and low levels of nutrients (such as calcium, nitrogen, and phosphorus). Serpentine soils do not hold water very well, so they tend to be dry. These soils are found on rocky outcrops scattered in Mediterranean biomes like those in California (Figure 22). The areas around the serpentine outcrops have very different soil, with more moisture and nutrients and lower levels of toxins. Plants on serpentine soils tend to be much smaller than plants of the same species growing on nearby non-serpentine soils.

Some strains (varieties) of plants that evolved in areas with serpentine soils have adaptations that allow them to deal with high levels of toxins and low levels of water and nutrients. Within one species, there can be strains that are tolerant to serpentine conditions and strains that are not. The serpentine-tolerant varieties usually do not evolve on one outcrop and spread to the other outcrops. The ability to tolerate serpentine soils tends to evolve independently in several places. This is an example of **convergent evolution**.

*Achillea borealis* and *Gilia capitata* are examples of species that can grow on either serpentine or non-serpentine soils. Researchers tested the performance of serpentine adapted and non-serpentine adapted strains on serpentine and non-serpentine soils (Figure 23).

**Evolutionary Perspective: Serpentine Soils and Plant Communities, cont.**

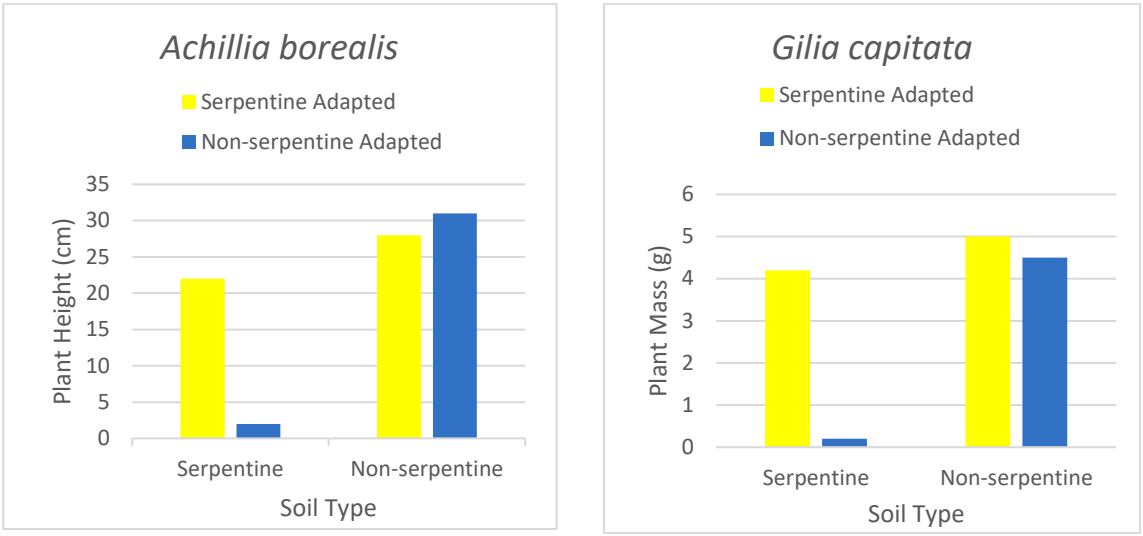



Figure 23. Plant size on serpentine and non-serpentine soil. Based on: Anacker, B.L. (2014). The nature of serpentine endemism. *American Journal of Botany*, 101:219-224.

**Analyze the Figure:**

- For *Achillia borealis,* does the soil type influence the plant height?
- For *Gilia capitata*, does the soil type influence the plant biomass?
- Is there a difference between serpentine-adapted and non-adapted plant performance?

**Check Your Understanding**

- How do nutrients enter and leave soil?
- How does soil pH influence soil nutrients?
- What might influence the pH of soil?

**Soil Organisms are Critical to Soil Function**

We have seen how organisms that live in soil can have a major influence on soil formation. They also keep the soil healthy. They break down plant litter to return nutrients to the soil, mix the soil, aerate it, and may even help plant roots access water and nutrients. If soil organisms are killed by fire or some other means, plants will start to use up the available nutrients and the plant litter will not be recycled. The re-population of soil organisms from nearby surviving soil communities is important to the recovery of an area.

In one study researchers measured the influence of soil decomposers and plant litter on the growth of birch trees in Finland. They heated humus until they killed all of the living things in it. They then placed it in 24 different containers about the size of waste baskets (17 cm in diameter, 30 cm tall). In half of the containers, they added soil organisms. The controls had no soil organisms. Sterilized litter from other tree species (silver birch leaves, alder leaves, Norway spruce wood, and rotten conifer wood) was added to the cylinders. In some treatments, these were mixed together. In others, they were left in separate patches. A birch seedling was planted in each container. After about 1 year, they measured the birch seedlings (Figure 24).

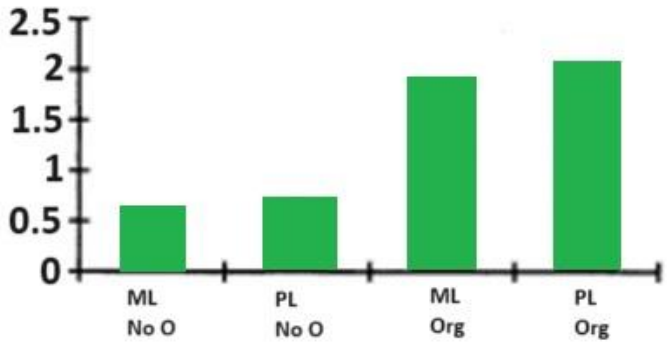



Figure 24. Dry mass of Birch (*Betula pendula*) grown in with different plant litter treatments, with and without soil organisms and. ML = Litter mixed together; PL = Litter left in patches; No O = no soil organisms added; Org = soil organisms added. Differences between No O and Org were significant ($P < 0.001$). Litter treatments were not. Modified from: Sulkava, P., Huhta, V., Laakso, J., & Gylén, E. R. (2001). Influence of soil fauna and habitat patchiness on plant (Betula pendula) growth and carbon dynamics in a microcosm experiment. *Oecologia*, *129*(1), 133-138.

**Analyze the Figure**

- Did addition of soil organisms influence birch growth?
- Did distribution of litter influence birch growth?

Just as soil organisms are critical to soil function, soil influences which organisms can live in an area. For more on this topic, see **Case Study Part 4. Why does Soil Matter?**

**Case Study Part 4. Why does Soil Matter?**

As we have seen, the amount and quality of the soil is critical for plant growth, but different species have different needs. The hardwoods that make up most of the New England forests can usually crowd out the jack pines, but they require deeper soil that is richer in nutrients and moisture.

Jack pines can grow in poor, dry soil. They grow best in open, sunny spaces, and are well adapted to the fires that are more common in dry areas. Their cones will not open without fire (this sort of adaptation will be discussed more in Chapter 16).

The jack pine barrens provide a home for various other species that are better adapted to the jack pine forest than the surrounding hardwood and mixed forest, such as the endangered Kirtland's warbler (Figure 25). The greater soil diversity leads to a greater species diversity.

http://en.wikipedia.org/wiki/Kirtland's_warbler#/media/File:Dendroica_kirtlandii_-Michigan,_USA_-male-8_(5).jpg

Figure 25. Kirtland's warbler (*Dendroica kirtlandii*).

**Learning from the Case Study**

- Why do the jack pines survive so far out of their normal range?
- How does the presence of jack pines influence the community?

**Check Your Understanding**

- How do soil organisms influence soil?
- Why might the soil organisms be different in different environments?
- How does soil influence which species can live in an area?

# Key Concepts

- Soil is composed of minerals, organic material, water and air
- Formation and structure of soil is determined by the soil community, climate and other factors
- Soil differs in color, particle size, nutrient content, pH and other factors that influence plant growth.
- Erosion by wind and water moves soil to areas where it is deposited
- The pH of soil influence its ability to retain nutrients
- Soil organisms are critical to soil formation and function

# Apply the Concepts

**Learning Outcomes**

1. *Accurately describe the composition of soil and why it varies under different conditions*
2. *Explain how soil is formed and how it is moved by erosion and deposition*
3. *Describe the importance of soil to the ecosystem*
4. *Accurately explain the development of soil horizons*
5. *Explain why soil nutrients and pH vary and why this is important*

1. Imagine that you were trying to help students at a local school grow a vegetable garden. The soil has a very high clay content. Your neighbor tells you that mixing dead plant material into the soil will improve your garden. How might that be helpful? *(Learning Outcome 1)*

2. Sinkholes are areas that suddenly collapse, leaving large holes in the ground (Figure 26). One way they can form is when there is a break in a water main (a large pipe bringing water to an area). Explain how an event like that could lead to a sinkhole. *(Learning Outcome 2)*

http://water.usgs.gov/edu/sinkholes.html

Figure 26. Aerial view of a sinkhole in a residential area.

3. Examine the soil colors in Figure 27.

https://www.nrcs.usda.gov/resources/education-and-teaching-materials/soil-colors-of-the-united-states

Figure 27. Map of soil colors (at a depth of 25 cm) in the continental United States (blue is water).

A. Describe some general patterns.
B. Explain these patterns, relating them to the influence of climate on soil.
C. Explain why not all soils in the same climate zone would look the same. (*Learning Outcomes 1 & 4*)

4. When a new house is constructed, the top layers of soil are often removed. If the homeowners want a lawn, they usually have to bring in truckloads of topsoil. Explain why grass might not grow well without the topsoil. *(Learning Outcomes 4)*

5. Imagine that a group wants to preserve a rare native plant. Why would it be important to grown it in its native soil rather than commercial potting soil? *(Learning Outcomes 3 & 5)*

# Unit III

# The Living World: Limits of Life

Burton 2003

Life zones at different altitudes in Kamchatka, Russia.

**Climate, elevation, and other physical factors determine where species live.**

**Unit Outcomes**

- Accurately describe conditions in different life zones
- Accurately apply ecological concepts to explain and predict abiotic and biotic properties of terrestrial and aquatic life zones
- Clearly explain how ecological and evolutionary factors lead to the distribution of species

# Chapter 8: Life Zones on Land: Biomes and Adaptations

## Case Study Part 1: Lessons from a Mountain

https://commons.wikimedia.org/wiki/File:The_Jungle_Ultra_Long_Stage.jpg

Figure 1. Tropical rainforest and river.

Imagine that you are setting out to climb a mountain in South America. You are near the equator. You take a boat trip to the foot of the mountains to start your adventure. Even though you are just sitting, you are uncomfortably hot and your skin feels sticky with sweat that will not evaporate in the humid air. Dense green forests line the wide, muddy river. When you land at a small clearing, you find that the ground is red-brown, sticky mud. There are so many types of plants that even your guide cannot name them all. Many birds call and insects buzz around you.

It seems odd to see your guide loading your pack with warm clothes for the climb ahead, but you know you will need them. As you climb, you will find yourself in very different climate zones. As you learn about each climate, consider what you would see on the mountain at different elevations.

**Learning from the Case Study**

- How do latitude, elevation, and proximity to the ocean explain the climate of this area?
- How does the climate explain the amount and type of plant life? What challenges must plants overcome in this warm, wet environment?
- Predict how the plant community will change as you increase your elevation.

# Learning Outcomes

1. *Make and defend valid predictions about biomes based on climate information*
2. *Make and defend valid predictions about productivity and soil based on climate*
3. *Explain how climate and soil influence which species can live in an area*
4. *Explain how biomes shape the anatomical, physiological, and behavioral adaptations of organisms*

**Vocabulary Toolkit**

**Roots**

Endo = In/inside
Ecto = Out/outside

**Opposites**

Endotherm and ectotherm

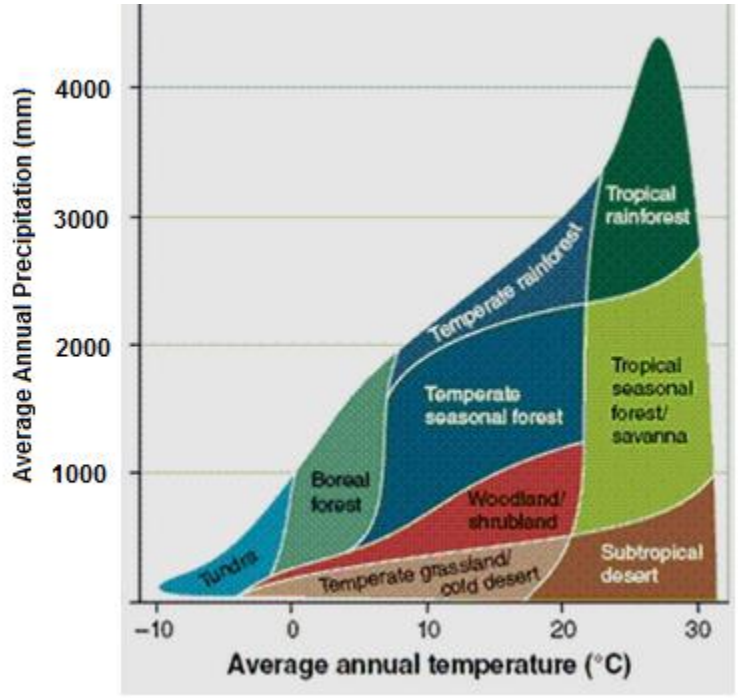
**Word Watch List**

**Biome**: Life zone created by climate and categorized by the dominant vegetation
**Temperate**: Seasonal climate found between the tropics and polar areas
**Tropical**: Climate with little or no seasonal variation in temperature, found near the equator
**Evapotranspiration:** Evaporation of water from plants, soil, and other surfaces into the atmosphere
**Gross Primary Productivity**: Amount of photosynthesis
**Net Primary Productivity**: Amount of new producer biomass made
**Biomass:** Amount of living material, usually measured as weight
**Canopy**: Top layer of trees in a forest
**Central tendency**: One number that represents a data set, defined in various ways, including the median or average (mean)
**Standard deviation**: Measure of variation in a data set
**Standard error**: Measure of variation in a data set—standard deviation divided by square root of the sample size
**Adaptation**: Short-term adjustment or long-term evolutionary change shaped by environmental factors
**Homeostasis**: Process of maintaining internal conditions within limits
**Perennial Plant:** Plant that lives for multiple years
**Annual Plant:** Plant that lives only a year or less. It usually dies after producing seeds
**Endothermic**: Refers to birds and mammals, which produce their own heat to maintain internal temperature
**Ectothermic**: Refers to most animals, which rely on the environment for heat
**Evolutionary Tradeoff**: The balancing of costs and benefits of a particular trait
**Behavioral thermoregulation**: Moving between microclimates to regulate body temperature
**Conifer**: Tree with cones for reproductive structures. Usually evergreens
**Deciduous**: Describes plants that usually lose most or all leaves each year

## Climates Create Distinct Biomes

As discussed in Chapter 7, climate varies greatly on Earth. This creates life zones that have distinctive collections of species that are adapted to those climates. Ecologists call these life zones **biomes** (or ecoregions). The biomes are named after the dominant type of vegetation and whether the climate is seasonal. **Temperate** climates have warm and cold seasons but are

not as extreme as the climates near the poles. Non-seasonal climates near the equator are **tropical**. The two key factors in determining the biome are temperature and rainfall (Figure 2).




Adapted from: http://en.wikipedia.org/wiki/File:PrecipitationTempBiomes.jpg

Figure 2. World biomes are a result of rainfall and temperature. Averages are used to classify locations. Some systems use more or different classifications.

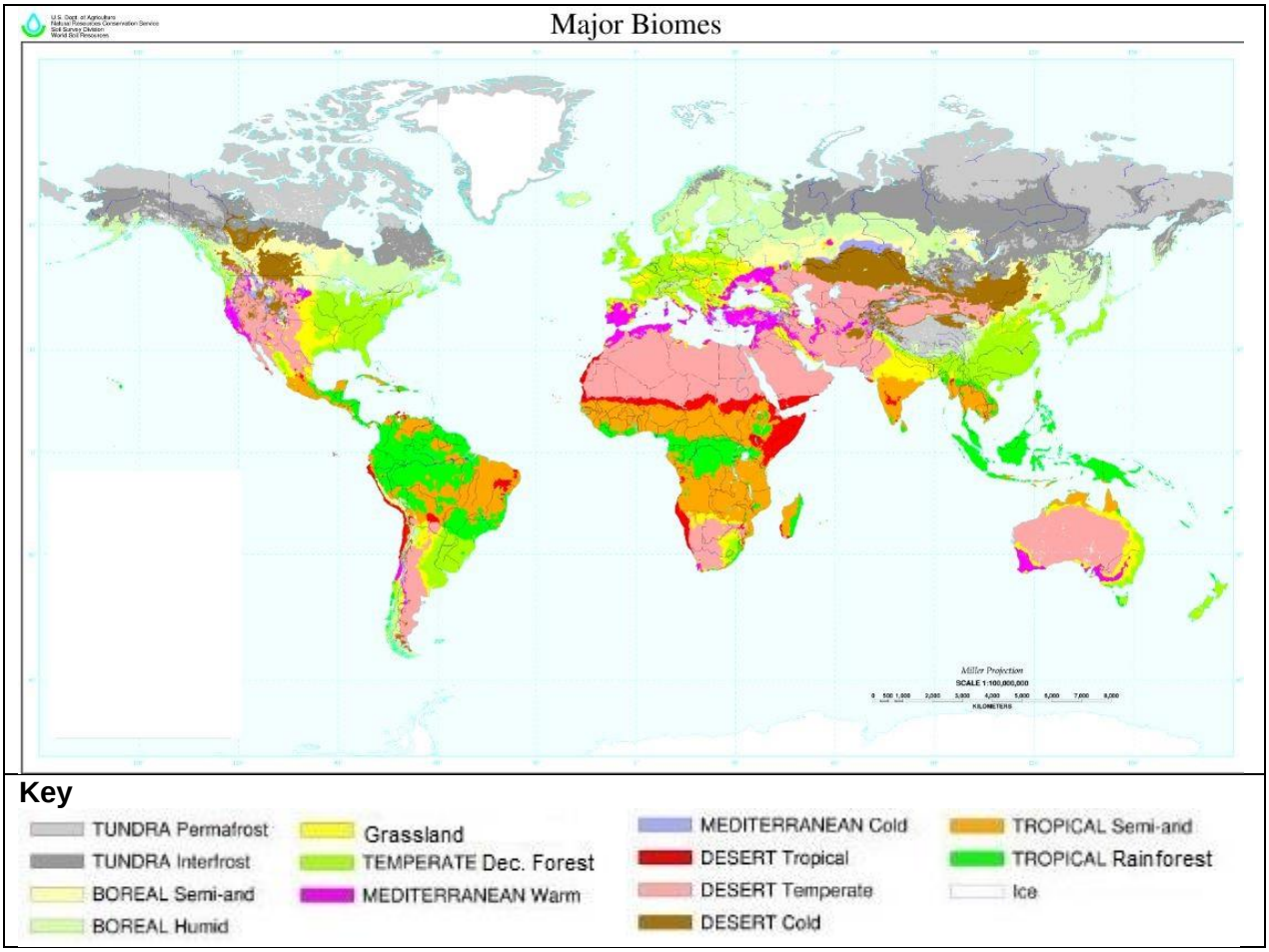
**Analyze the Figure**

- If an area has an average annual temperature of 15 ºC, and an annual precipitation of 1500 mm, what biome would it be?
- If an area has an average annual temperature of 10 ºC, what determines what biome it would be?
- Why isn't there a biome for an area with an average annual temperature of -5 ºC, and an annual precipitation of 1500 mm?

There are many valid systems for dividing the Earth into different zones. Some have many categories and sub-categories. This chapter will use relatively few categories. The variation in systems reflects different decisions about categorizing the complexity of Earth's climates.

As discussed in Chapter 6, climates are the result of a region's location on Earth (Figure 3). As you look at global distribution of different biomes, what patterns do you see? While it is useful to group life zones into general categories, such as "desert" and "grassland," the natural world rarely fits neatly into the categories that humans create. The categories hide a lot of variation. For example, your town may have a very different climate from another location that is shown as

the same color on this map. There is variation in the species in each biome, but all areas in the same biome share several characteristics. For more on how areas are categorized into biomes, see **Taking It Further: Using a Dichotomous Key of Biomes**. For more on how changing climate might alter biomes, see **Hypothesis Testing: What Does it Take to Convert the Boreal Forest Biome?**




Modified from: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/maps/?cid=nrcs142p2_054002

Figure 3. World biomes. Different systems may use more or fewer categories.

**Analyze the Figure**

- Do biome patterns tend to follow latitude or longitude more?
- Which biome is located near the equator?
- What biomes tend to be right next to tropical rainforest biomes?

**Do Try this at Home: Identifying Biomes**

Come up with an ecologically valid name for your local life zone. Are there distinct warm and cold seasons? Is your area very dry? Take a look at the native plants in your city or town. Is the vegetation pretty much like it was 100 years ago, or were things very different before European settlement? If you are surrounded by agricultural fields, your area may once have been grasslands. Are there trees? Are most of them conifers or deciduous, or is there a mixture?

When you have a reasonable name, use the Internet to search for your state's biomes (or ecoregions) and see how scientists have classified your home.

**Taking It Further: Using a Dichotomous Key of Biomes**

Scientists use keys to identify species, soil types, and other things. Dichotomous keys offer two choices at each step. Use this key to classify a biome. For example, if the answer to Number 1 is "low," go to step 2 and continue. If the answer to number 1 is "moderate," skip to step 8 and proceed from there. Not every location will fit neatly. This key divides biomes into more varieties than those described earlier. Other systems may describe even more biomes.

| | | |
|---|---|---|
| 1. | A. Precipitation low (< 400 mm/year or < 500 mm if cold) | 2 |
| | B. Precipitation moderate to high | 8 |
| 2. | A. **Average** temperature Low (< 10 $^{o}$C) | 3 |
| | B. **Average** temperature > 10 $^{o}$C | 5 |
| 3. | A. Below 0 $^{o}$C all year | **Permanent Ice** |
| | B. Below 0 $^{o}$C 2-7 months of the year | 4 |
| 4. | A. **Maximum** temperature < 10 $^{o}$C, no dry season | **Tundra** |
| | B. **Maximum** temperature approx. 10 $^{o}$C, dry season in winter | **Subarctic** |
| 5. | A. **Maximum** temperature 10--20 $^{o}$C, some months < 0 $^{o}$C | **Temperate Shrubland** |
| | B. **Maximum** temperature > 22 $^{o}$C | 6 |
| 6. | A. **Minimum** temperature < 0 $^{o}$C, seasons, most precip. snow | **Temperate Desert** |
| | B. **Minimum** temperature > 0 $^{o}$C | 7 |
| 7. | A. Monthly average temperature sometimes < 10 $^{o}$C | **Tropical Shrubland** |
| | B. Annual precipitation < 200 mm, dry all year, very hot | **Tropical Desert** |
| 8. | A. **Maximum** temperature between 10 - 20 $^{o}$C | 9 |
| | B. **Maximum** temperature > 20 $^{o}$C (lower if dry, higher if wet) | 12 |
| 9. | A. Annual precipitation > 1000 mm, **minimum** Temp. > 0 $^{o}$C | **Temperate Rainforest** |
| | B. Annual precipitation < 1000 mm | 10 |
| 10. | A. Precipitation 510-1020 mm, approximately = evap. | **Grassland** |
| | B. Precipitation 500-2500 mm, greater in summer | 11 |
| 11. | A. Months above 10 $^{o}$C = 4-7, **maximum** temperature < 22 $^{o}$C | **Temperate Deciduous** |
| | B. Months above 10 $^{o}$C = 8, **max.,** temp. > 22 $^{o}$C, no freezing | **Subtropical Forest** |
| 12. | A. Precipitation < 1500 mm/year | 13 |
| | B. Precipitation high, > 1500 mm/year | 14 |

**Continued**

**Taking It Further: Using a Dichotomous Key of Biomes, cont.**

| | | |
|---|---|---|
| 13. | A. Dry season in summer, wet winter, temperature seasonal | **Mediterranean** |
| | B. Two month dry season in winter, **minimum** temp. > 18 $^{o}$C | **Savanna** |
| 14. | A. Seasonal, 6-9 months below 0 $^{o}$C, **maximum** temp. < 22 $^{o}$C | **Temperate Deciduous** |
| | B. Never < 0 $^{o}$C, **average** temperature approx. 27 $^{o}$C | **Tropical Rainforest** |

**Check Your Understanding**

- What are the two main factors used to assign an area to a biome?
- Which influences general biome patterns more, latitude or longitude?
- Predict how the plant communities of any two of the biomes might differ.

**Warm, Wet Biomes are More Productive**

Recall from Chapter 4 that photosynthesis requires light (for energy), water, and carbon dioxide. Carbon dioxide level does not usually vary between the biomes, but the cost of getting the carbon dioxide does. A plant has to open the small pores in its leaves to get $CO_2$. This allows water to evaporate from the plant—a process called **evapotranspiration**. Evapotranspiration is what allows plants to draw water and other materials up from their roots, but in dry climates this water loss can be costly.

The amount of photosynthesis occurring in producers is **gross primary productivity**. Some of the productivity will be used to meet the needs of the producer, including active transport and synthesis of complex molecules. **Net primary productivity** the amount of **biomass** (mass of living tissue) produced. Because it is difficult to measure the roots of plants, most studies measure only aboveground biomass. (See Chapter 5: Measuring Productivity for more information.) Evapotranspiration will increase with sunlight and water availability, two factors necessary for photosynthesis, so it is reasonable to expect evapotranspiration and productivity to be correlated (Figure 4).

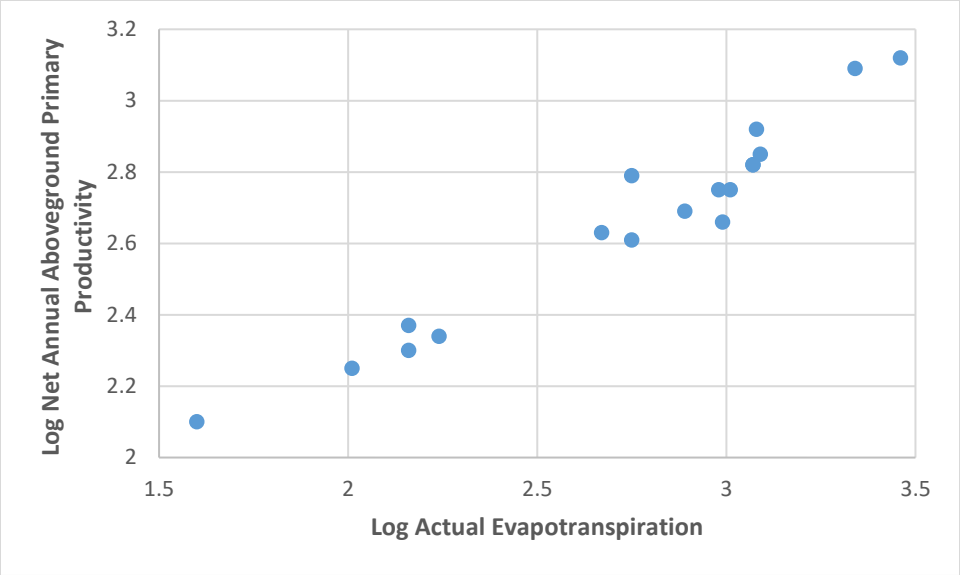



Figure 4. Log of evapotranspiration and log of net aboveground plant productivity per square meter per year. Each dot represents a different environment. Evapotranspiration is a function of both the available water and the available heat to evaporate that water off of plants. The log of units is used when the variation in scale is large. Based on: Rosenzweig, M. L. (1968). Net primary productivity of terrestrial communities: prediction from climatological data. *American Naturalist*, 67-74.

**Analyze the Figure**

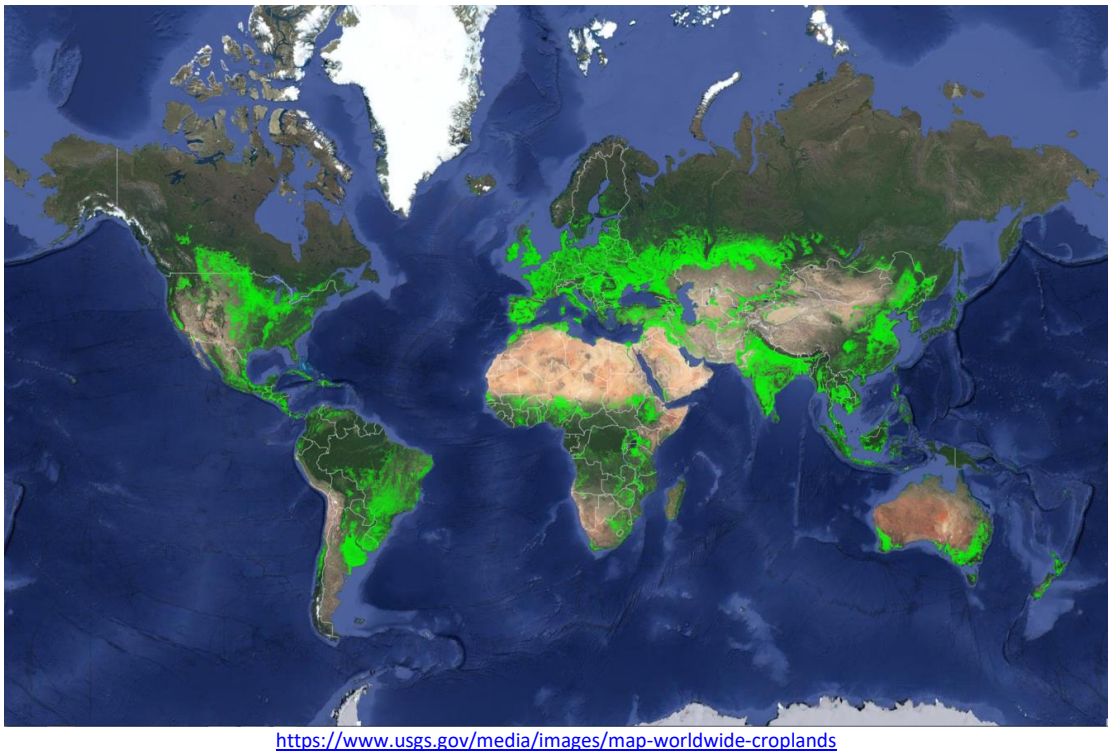
- What is the main pattern of the data?
- How would you explain this pattern?
- Do you predict that productivity at 5000 mm of evapotranspiration per year would be higher, lower, or about the same as the productivity at 3500 mm per year? Explain your answer.

Both precipitation and temperature must be considered together. Tropical rainforests have high inputs of water and energy so they have high productivity per unit area. An area with high precipitation but low temperatures would have lower productivity because the water would stay frozen for a large part of the year. An area with high temperatures but little rainfall—deserts—would have very low productivity. Fertility of the soil—its nutrient content—is also a major factor in productivity. Higher productivity can also lead to greater diversity—having more species.

**Check Your Understanding**

- How are photosynthesis and productivity related?
- What factors can limit productivity?
- Which biomes are most and least productive?

**Why It Matters: Climate, Soil, and Food**



https://www.usgs.gov/media/images/map-worldwide-croplands

Figure 5. Map of agricultural regions of the world. The brightest green areas produce the most crops. Tan areas have the least crop production value because of factors such as cold temperatures, low precipitation, or lack of appropriate soil. Land that is marginal for crop use may be used for raising livestock.

According to the United Nations, about 1 billion people are malnourished. Waste, distribution problems, and economic justice are parts of this issue. However, understanding the relationship between climate, soil, and the food supply of the world is essential to reducing malnutrition.

Notice that some of the most important croplands in Figure 5 correspond to the grasslands in Figure 3. These areas usually have very good soil (see Chapter 7). The fairly low precipitation in grasslands can be supplemented by irrigating the fields with additional water. There are some side effects of this, such as using up water sources, adding salt and other minerals to the soil, and possibly increasing erosion.

- Low nutrient levels in soil can be increased using fertilizer. However fertilizer can end up in water supplies, leading to environmental and health issues. Should this be regulated in developing countries?
- Should high productivity biomes be used for growing livestock, such as cattle and pigs, or growing more crops for people?
- Should genetically modified crops be used to increase productivity in marginal areas?
- How does stability of the food supply influence political stability?

**Each Biome has Both Distinctive Features and Variation**

Categorizing areas by their biome is very useful for ecologists. Knowing the biome allows us to make many predictions about the soil, productivity, variety of organisms, and other important factors. Research done in a biome may be relevant to research done in other areas in the same biome.

Any category will also hide a lot of variation. For example, all deserts are dry, but some are hotter or colder. The organisms that evolved in one desert will be different than those that evolved in a different desert. The soil may come from different rocks or other sources. So a label such as “desert” both tells a lot about a region and hides a lot of information about how it differs from other areas with the same label. Even within the same desert, microclimates will lead to variation. To learn more about capturing the main trend and variation in data, see **Model Skill: Descriptive Statistics**.

In the following tables, you will be applying the general principles about climate, soil, and productivity to analyze biomes. Pay attention to both similarities and differences between and within the photographs.

Table 1. Earth's biomes.

**Tropical Rainforest in Costa Rica**

http://www.ecolibrary.org/

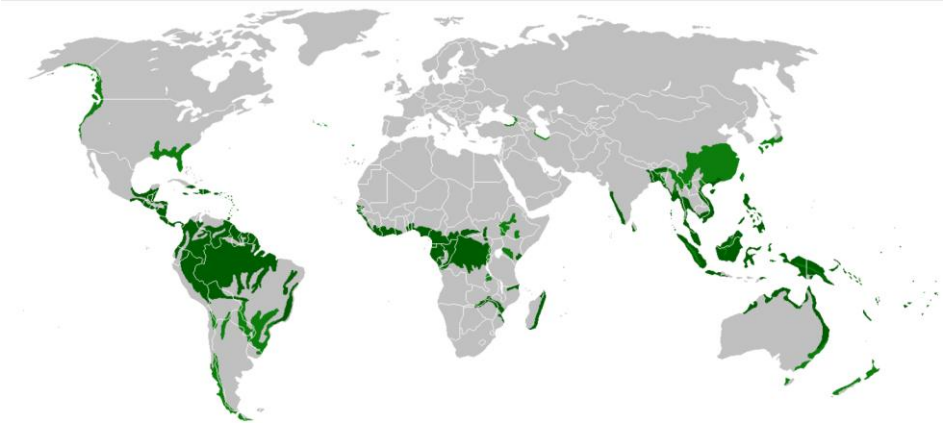
**Tropical Rainforest in Queensland, Australia**

https://en.wikipedia.org/wiki/Tropical_rainforest#/media/File:Rain_Forest_Daintree_Australia.jpg

**Analyze the Figures:**

- Are the trees and smaller plants crowded close together? Do the tops of trees form a **canopy** over the other plants?
- Are there many types of plants visible?
- Would you predict that this biome has high or low productivity? Why?
- Would you predict that the soil has high or low levels of nutrients? Why?
- What differences do you see between the two rainforest sites?

**Tropical Rainforest Regions**



By Ville Koistinen (User:Vzb83) - Image:Vegetation.png, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1701729

**Sonoran Desert in Arizona, USA**

http://www.ecolibrary.org/

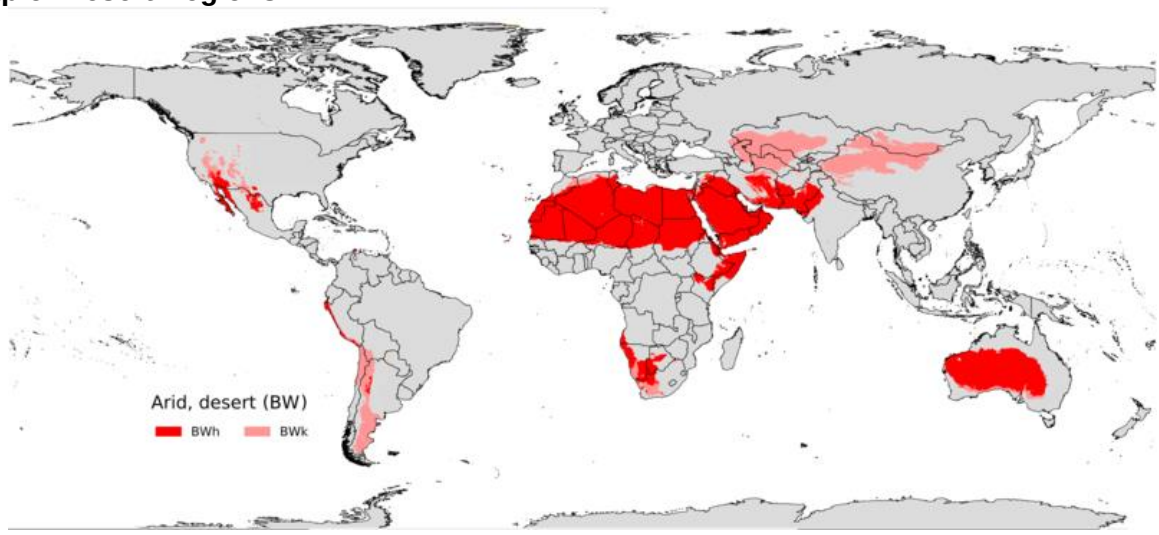
**Namib Desert in Namibia**

https://en.wikipedia.org/wiki/Desert#/media/File:Thorn_Tree_Sossusvlei_Namib_Desert_Namibia_Luca_Galuzzi_2004a.JPG

**Analyze the Figures:**

- Are the plants crowded close together or is bare ground visible?
- Are there many types of plants visible?
- Would you predict that this biome has high or low productivity? Why?
- Would you predict that the soil has high or low levels of nutrients? Why?
- What differences do you see between the two desert sites?

**Map of Desert Regions**




https://commons.wikimedia.org/wiki/File:BW_climate.png

**Temperate Rainforest in Washington, USA**

http://www.ecolibrary.org/

**Temperate Rainforest in Tasmania, Australia**

https://en.wikipedia.org/wiki/Forest#/media/File:Hellyer_Gorge,_Tasmania.jpg

**Analyze the Figures:**

- Are the plants crowded close together or is bare ground visible (aside from the path)?
- Are there many types of plants visible?
- Would you predict that this biome has high or low productivity? Why?
- Would you predict that the soil has high or low levels of nutrients? Why?
- What differences do you see between the two temperate rainforest sites?

**Map of Temperate Rainforest Regions**

https://en.wikipedia.org/wiki/Temperate_rainforest#/media/File:Temperate_rainforest_map.svg

**Grassland in Kansas, USA**

https://commons.wikimedia.org/wiki/File:Konza.jpg

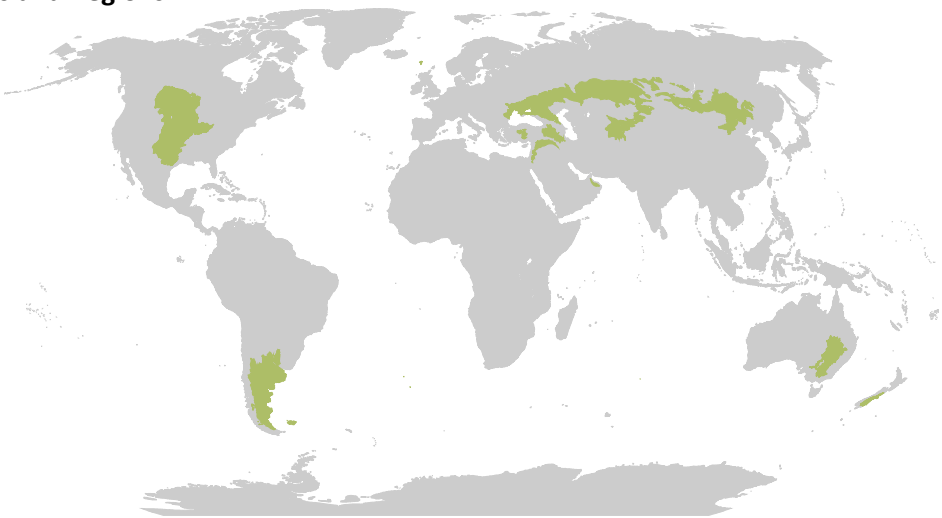
**Grassland in Tanzania**

https://en.wikipedia.org/wiki/Serengeti_National_Park#/media/File:Serengeti-Landscape-2012.JPG

**Analyze the Figures:**

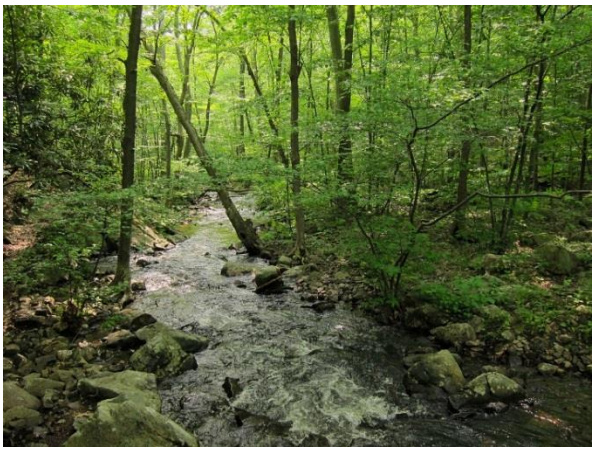
- Are the plants crowded close together or is bare ground visible?
- Are there many types of plants visible?
- Would you predict that this biome has high or low productivity? Why?
- Would you predict that the soil has high or low levels of nutrients? Why?
- Is fire likely to be common in this biome? What evidence led to this prediction?
- What differences do you see between the two grassland sites?

**Map of Grassland Regions**



By Terpsichores - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=22441318

**Temperate Deciduous Forest in New Jersey, USA**



https://en.wikipedia.org/wiki/Northeastern_coastal_forests#/media/File:Posts_Brook_from_Norvin_Green_State_Forest_Lower_Trail.jpg

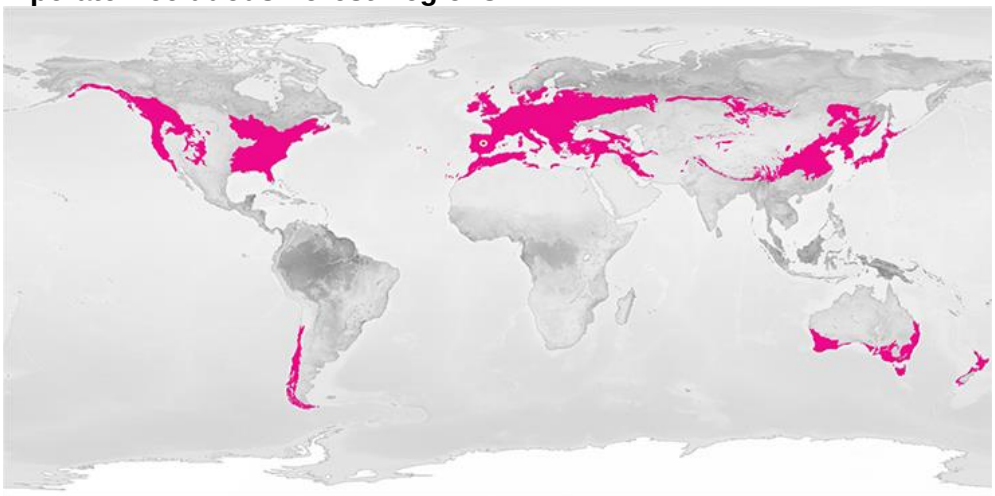
**Temperate Deciduous Forest in Germany**

https://en.wikipedia.org/wiki/Temperate_deciduous_forest#/media/File:Mixed_forest_NE-Germany.JPG

**Analyze the Figures:**

- Are the plants crowded close together or is bare ground visible?
- Are there many types of plants visible?
- Would you predict that this biome has high or low productivity? Why?
- The photograph from Germany was taken in early spring. Would these scenes look very different in different seasons?
- What differences do you see between the two deciduous forest sites?

**Map of Temperate Deciduous Forest Regions**



https://earthobservatory.nasa.gov/biome/maptemperate.php

**Boreal Forest in Alaska, USA**

https://en.wikipedia.org/wiki/Birds_of_North_American_boreal_forests#/media/File:Picea_mariana_taiga.jpg

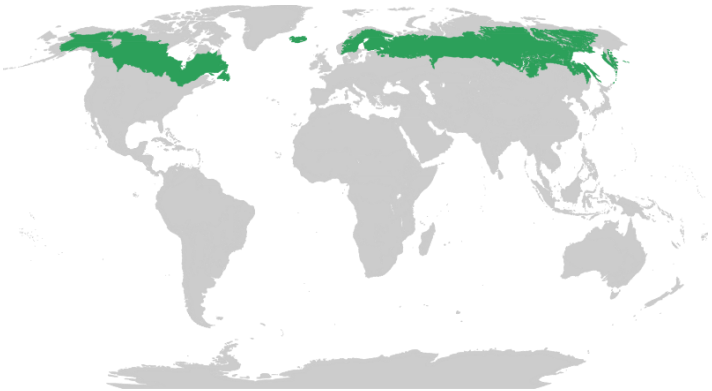
**Boreal Forest in Swiss Alps**

https://en.wikipedia.org/wiki/Forest#/media/File:Swiss_National_Park_131.JPG

**Analyze the Figures:**

- Are the plants crowded close together or is bare ground visible?
- Are there many types of plants visible?
- Would you predict that this biome has high or low productivity? Why?
- Would you predict that the soil has high or low levels of nutrients? Why?
- Would these scenes look very different in different seasons?

**Map of Boreal Forest Regions**

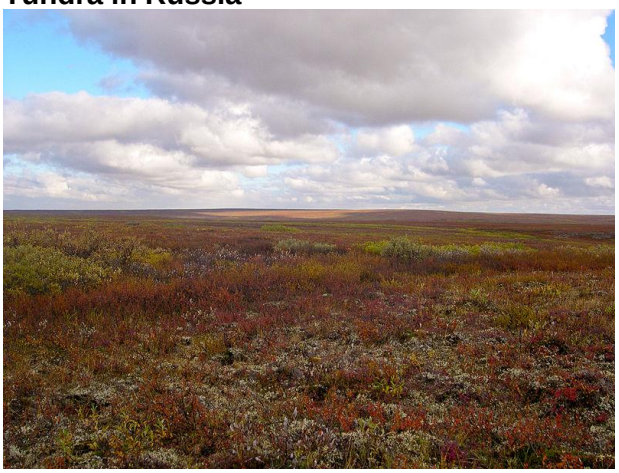


https://commons.wikimedia.org/wiki/File:Biome_map_06.svg

**Tundra in Alaska, USA**

https://commons.wikimedia.org/wiki/
File:Nunavut_tundra_-c.jpg

**Tundra in Russia**

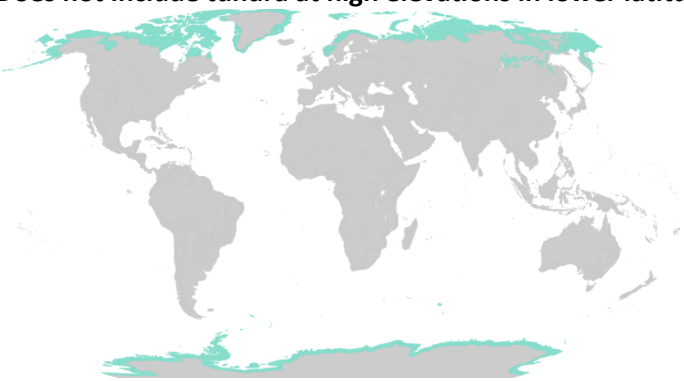


https://commons.wikimedia.org/wiki/
File:Bolshezemelskaja_tundra_1.JPG

**Analyze the Figures:**

- Are the plants crowded close together or is bare ground visible?
- Are there many types of plants visible?
- How tall would you predict the tallest plants are?
- Would you predict that this biome has high or low productivity? Why?
- Would you predict that the soil has high or low levels of nutrients? Why?
- Would these scenes look very different in different seasons?
- Are there many differences between the two tundra sites?

**Distribution of Tundra. Does not include tundra at high elevations in lower latitudes.**



https://en.wikipedia.org/wiki/Tundra#/media/File:Biome_map_11.svg

**Permanent Ice on Mountain in Wyoming, USA**

https://en.wikipedia.org/wiki/List_of_glaciers_in_the_United_States#/media/File:Gannet_Peak_with_Gannett_Glacier.jpg

**Permanent Ice in Greenland**

https://en.wikipedia.org/wiki/Apusiaajik_Glacier#/media/File:Apusiaajik-glacier.jpg

**Analyze the Figures:**

- Are any plants visible?
- Would these scenes look very different in different seasons?
- Are there many differences between the two permanent ice sites?

**Map of Permanent Ice Regions, not including mountaintops**

https://commons.wikimedia.org/wiki/File:Biome_map_Rock_and_Ice.svg

**Model Skill: Descriptive Statistics**

If you were to choose only one or two numbers to describe the climate in your home town, what would you use? One number that you have seen is the average annual temperature. For example, the average annual temperature in Park City, Utah (Chapter 6, Figure 17) was given as 9.6 ºC. An average (mean) is one way to measure the **central tendency** of a set of data. To obtain an average, one merely adds up the data points and divides by the number of data points there are. The number of data points is called the sample size.

Table 2. Average monthly temperatures and precipitation for Park City, Utah.

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Temp. (ºC)** | -3 | 0 | 4.1 | 8.8 | 13.3 | 18.6 | 23.2 | 21.7 | 16.7 | 10.3 | 3.3 | -2 |
| **Precip. (mm)** | 39 | 37.3 | 40.2 | 47.5 | 41.3 | 24.6 | 16.2 | 24.4 | 24.9 | 36.2 | 34.7 | 42.4 |

If you add up the temperature values in Table 2 and divide by 12, you will find the average monthly temperature of roughly 9.6. Even though February is zero, it is added into the sum and the sample size. Averages can be influenced a lot by one extreme value.

Another way to measure the central tendency is the median. The median tells you which value is in the middle of your data set, so that half of the values are below it and half are above it. To find the median, first put all of the values in numerical order:

Table 3. Ordered temperature values from Table 2.

| **Order** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Temp. Values** | -3 | -2 | 0 | 3.3 | 4.1 | 8.8 | 10.3 | 13.3 | 16.7 | 18.6 | 21.7 | 23.2 |

If we had an odd number of values in the table the mean would be the middle value. Since this data set has an even number of values, you would select the average of the two middle values ((8.6 + 10.3)/2) = 9.55 ºC. In this case, the mean and median are fairly similar. This is because there was not an extreme outlier for temperature.

The mean precipitation is 42.4 mm per month, while the median is 36.8 mm. The very high value for April influences the average, but doesn't influence the median any more than it would if it were 42.4 (the value of the next-highest precipitation).

Variation is a very important factor in climate. There is a lot of difference between a climate that has a daily average of 9 or 10 ºC every day and one that varies from -20 ºC to 30 ºC, even though they may have the same annual average.

**Continued**

**Model Skill: Descriptive Statistics, cont.**

One statistic that quantifies the variation in a data set is the **standard deviation**. It measures how much each data point varies (deviates) from the mean (standard). People usually use software to obtain a standard deviation (it is calculated by subtracting each value from the mean, squaring the result, finding the mean of these numbers, and taking the square root of that mean). The standard deviation of the temperature data for Park City is 9.2. Another common way of stating the amount of variation is the **standard error**. This is the standard deviation divided by the square root of the number of data points or sample size. The square root of 12 is 3.46. In this case, the standard error is 9.2/3.46, or 2.66.

A lot of the variation in temperature and precipitation has already been smoothed out in the data set, which is based on 20 years of average daily temperatures. Think about one day, such as your birthday. The temperature probably varied from midnight to midnight on that day. All of that information was compressed into a daily average. Some of your birthdays may have been very hot or cold, but all are averaged to give one number to represent what the temperature *usually* is on your birthday. A high standard deviation would indicate that it varied a lot from year to year.

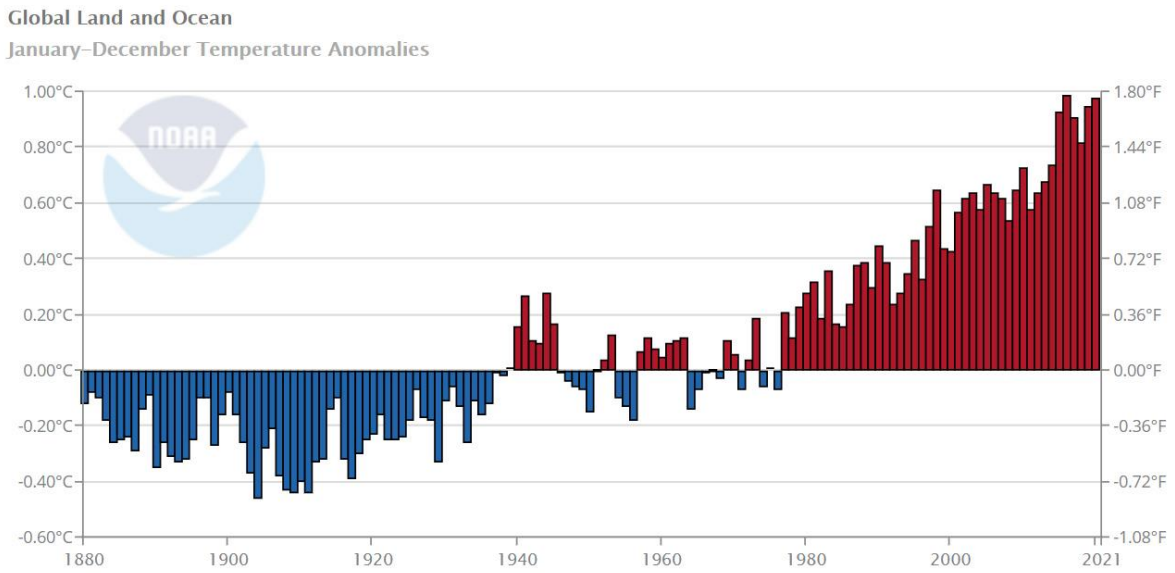
What are the median and mean temperatures for the data set in Table 4? What are the standard deviation and standard error of the temperature?

Table 4. Average climate data for Petropavlovsk, Kamchatka, Russia.

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Temp. (ºC)** | -8.6 | -8.4 | -5.5 | -1.1 | 2.9 | 7.4 | 11.3 | 12.4 | 9.5 | 4.4 | -2 | -6.4 |
| **Precip. (mm)** | 60.3 | 47.6 | 57.4 | 45.5 | 49.1 | 56.8 | 78.4 | 90.2 | 86.2 | 91.8 | 64.9 | 63 |

**Misconception Alert: A cold winter day, or even a colder year is evidence against a trend of rising temperature.**

**FALSE.** It is possible to have a very cold day during a very warm year or decade. Even if the average and median temperatures are generally increasing, there will still be variation in temperatures. Figure 6 shows temperature anomalies—differences between any particular year and the long-term average. While annual temperatures vary, the overall trend is annual temperatures increasing, compared to the average.




https://www.climate.gov/maps-data/dataset/global-temperature-anomalies-graphing-tool

Figure 6. Global average (0 line) and annual temperature anomalies (blue bars are below average, red bars are above average) from 1880 to 2021.

**Check Your Understanding**

- What are some key ways that biomes differ?
- How can areas in very different places have the same biome?
- Why might specific places in the same biome still be different?

**Hypothesis Testing: What Does it Take to Convert the Boreal Forest Biome?**

Boreal trees are specifically adapted to cold temperatures and short growing seasons caused by freezing. They grow slowly and resist water loss. Changes in temperature or precipitation could change boreal forest into tundra, steppe (grassland), shrubland or other forest types (Figure 2). The warming rate of boreal forest regions is about twice as fast as the average warming of the rest of the world. Will temperature increases convert the boreal forest biome to other biomes?

If warming converted the boreal forest into another biome, would the change be gradual and easily reversed, or would there be "thresholds" that would trigger a positive feedback loop and a rapid change? For example, snow reflects light, keeping an area cool. Darker surfaces absorb light and release the energy as heat (see Chapter 6). Warming can reduce snow cover, leading to even more warming. If precipitation decreases, water stress may cause some trees to die or lose needles. This exposes the forest plants and litter to sun and wind, drying them out and increasing the risk of fire, which will further thin the tree population.

To understand thresholds better, imagine a marble on a track. If the track is flat, pushing the marble will move it a distance that is proportional to the push. If the track has high and low spots, the marble will tend to stay in the low areas. A big push will be needed to move the marble over the threshold (high spot) to a new low spot. The low spots are stable states because the marble tends to stay in them. Are biomes stable states, or like low spots on a flat track?

Hypothesis 1: Changes in temperature and precipitation cause a gradual and proportional change from boreal forest to another biome.

Hypothesis 2: Biomes are stable states. Critical temperature and precipitation thresholds abruptly change boreal forest biomes to another biome.

Scheffer et al. (2012) used long-term data sets (1961-2002) to study plant cover patterns in the zone between 45$^{o}$ N and 70$^{o}$ N latitude. Much of this area is boreal forest, but examining the area on a smaller scale reveals a mix of plant communities. A key difference between the biomes is the percent tree cover. Tundra and steppes are mostly treeless. Sparse savanna and dense savanna have progressively more trees (about 20% and about 40% tree cover). The boreal forest has dense tree cover (about 75%). Tundra is typical in colder areas. Savannas are usually in areas that are drier than boreal forests. Warmer, drier areas are usually steppes.

The researchers analyzed biome type as a function of precipitation and mean July temperatures. Using the highest annual temperature (rather than an annual average) can be more informative in explaining limits of cold-adapted plants. They found that locations with the same mean annual precipitation and similar temperatures can have different plant communities. One reason might be the history of the site. For example, mature trees might survive in an area where their seedlings would not survive. So even if there were slight shifts in climate, it might not change the type of mature forest. A site might also be in the process of recovering from a disturbance, like a fire. (This topic will be discussed more in Chapter 16.) The soil type or depth might influence tree density. Other factors, like daylength, parasites, or seed predators could also influence the plant community.

Think about pushing the marble on the track again. If you took a photos of the marble at regular intervals, what pattern would you see in the flat and bumpy tracks? On the flat track, you might have an equal number of pictures for every spot on the track. Or you might have a smooth trend from one end to the other. The bumpy track would yield many pictures from the low spots and

very few from the high spots in between. In the actual data set, each point is a snapshot of a tree density in a community at a particular time. If the change from one biome type to another were gradual, we would expect to see a smooth distribution of tree density. If biomes are stable states, there would be a lot of data points at those tree densities and few data points of areas that were between these stable states. Analysis of tree cover frequency showed that there are 4 distinct peaks of tree cover (Figure 7).

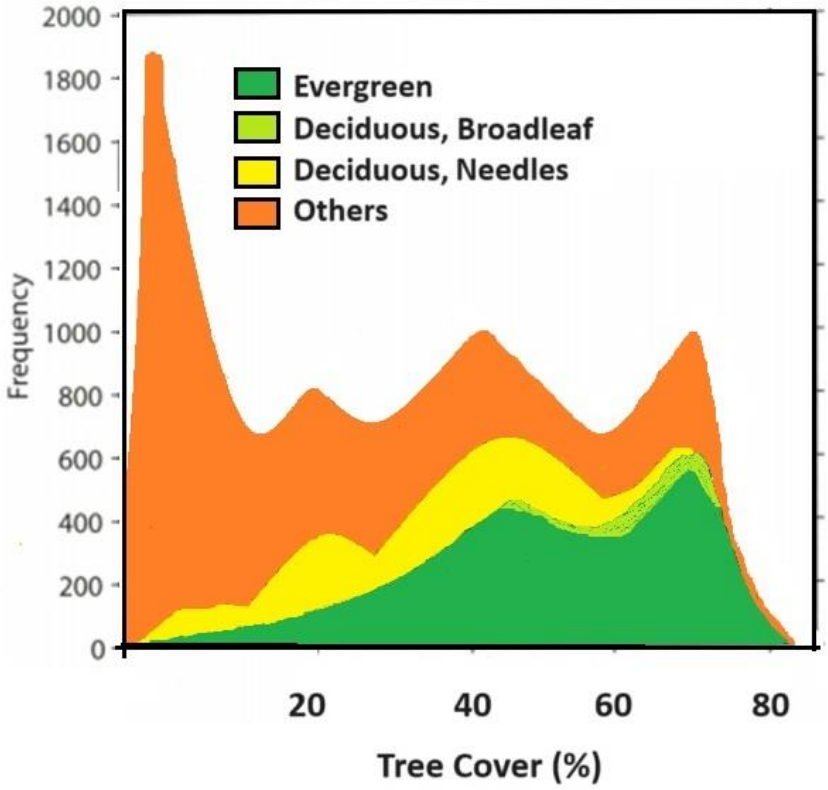



Figure 7. Distribution of frequency of tree cover patterns. Modified from: Scheffer, M., Hirota, M., Holmgren, M., Van Nes, E., & Chapin, F. (2012). Thresholds for boreal biome transitions. *Proceedings of the National Academy of Sciences of the United States of America, 109*(52), 21384-21389.

**Analyze the Figure**

- What are the 4 most common tree densities (approximately)?
- When tree cover is dense, what kind of trees make up most of the community?

**Evaluate the Hypotheses**

- Can either hypothesis be supported or refuted with the data given? Explain your answer.
- What other data would help to evaluate these hypotheses? Explain how you would use it.

**Organisms Adapt to Maintain Homeostasis**

The response of organisms to their environment is called **adaptation**. Adaptation can be short-erm adjustments in an individual or evolutionary changes in populations. These are very different processes.

Each biome presents challenges to the organisms that live there. Species have optimal and tolerable limits that are based on their physiology. On land, temperature and water balance tend to be major challenges. For example, if the organism is too cold, chemical reactions will be very slow, perhaps too slow to support life. Recall that ice expands as it freezes. This can destroy cell membranes. Too much cellular damage is deadly. If organisms are too hot, enzymes can be destroyed, killing the organism. An organism maintains itself through keeping various levels within tolerable limits. The process of maintaining the internal environment is called **homeostasis**. Individuals can adjust their behavior, physiology, and even anatomy during their own lives to maintain homeostasis, but these adjustments are *not* passed on to the next generation.

Evolutionary adaptations are genetic traits that have been shaped over generations. As discussed in Chapter 4, change in gene frequencies in a population is evolution. It can occur due to natural selection when individuals with certain genetic variations leave more offspring than other members of the same population. For example, organisms that live in hot environments have traits that help them to be successful in hot environments because these adaptations helped their ancestors to be successful. Often the traits that are useful in a particular environment evolve separately in different parts of the world. This is discussed in **Evolutionary Perspective: Ecological Equivalents**.

**Misconception Alert: Adjustments that animals make during their lives are passed to their offspring.**

**FALSE.** Individuals may make many adjustments to their environment. This does not change the DNA that is passed to the next generation. Only random mutation will cause a change in the DNA.

Organisms do inherit their *ability to make adjustments*. The ways they adjust and how much they can change are based on their genes, which have been shaped by their evolutionary past. For example, lions have inherited a physiological mechanism that adjusts mane growth in response to environmental temperature.

Mature male lions (Figure 8) can have very long thick manes. These manes attract females, but they can also cause the males to overheat. Male lions kept in zoos in warm climates have thinner manes than lions kept in zoos in cold climates (Figure 9). This is *not* because of the evolution of thinner manes in warmer zoos. Lions are intentionally traded between zoos to avoid inbreeding, so the lions in warm zoos may have parents from cold zoos, and vice versa. The

difference in mane growth is an adjustment made during the lions' lifetimes. It does not change the genes that the lions pass to their offspring.

http://en.wikipedia.org/wiki/Lion#/media/File:Lion_waiting_in_Namibia.jpg

Figure 8. Mature male lion (*Panthera leo*) with a full, dark mane.

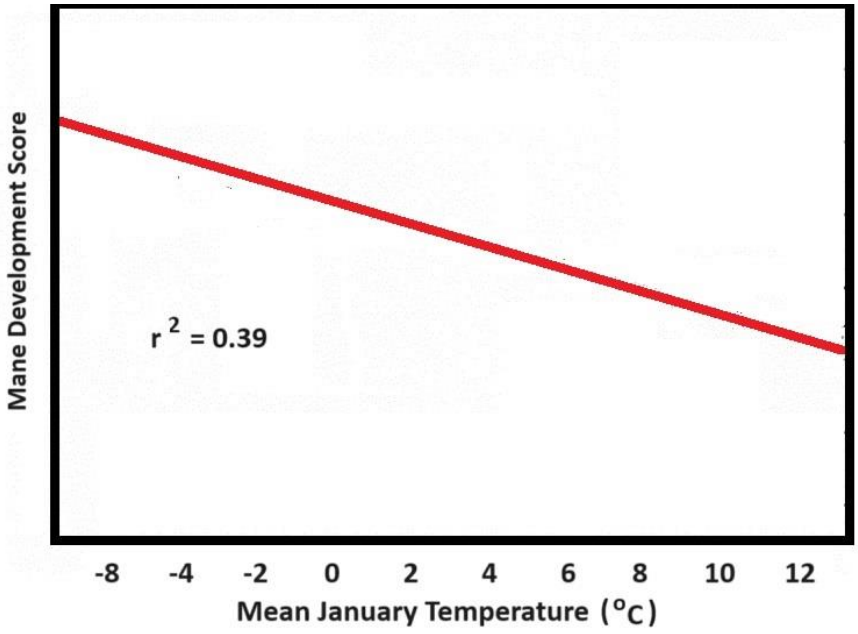



Figure 9. Male lion manes compared to mean January temperatures of the zoos where the lions live. Length, density, and color of the mane are all combined for the overall score. The larger the $r^2$ value, the stronger the correlation is. Based on: Patterson, B. D., Kays, R. W., Kasiki, S. M., & Sebestyen, V. M. (2006). Developmental effects of climate on the lion's mane (Panthera leo). *Journal of Mammalogy*, *87*(2), 193-200.

**Analyze the Figure**

- What is the overall relationship between mean January temperature at the zoo and the lion mane score?
- Is the red line a model, or the actual data for each temperature?
- Would you predict that there is variation in mane density at zoos with the same mean January temperature?

**Evolutionary Perspective: Ecological Equivalents**

https://en.wikipedia.org/wiki/Barrel_cactus#/media/
File:Echinocactus_grusonii_1.jpg

https://commons.wikimedia.org/wiki/
File:Euphorbia_obesa_222.JPG

Figure 10. Two species of plants that are adapted to desert biomes.

Two major reasons species look and function as they do are their evolutionary history and their environment. The two plants in Figure 10 are protected by sharp spines that provide some shade and discourage herbivores from eating their precious tissues. Neither one has leaves because leaves increase water loss. Both have folds that allow them to expand when water is available. You probably had no trouble identifying these plants as desert species. If you assumed they were close relatives, you were wrong. The plant on the left is a cactus, native to the Americas. The plant on the right is a Euphorbia, native to Africa. Both plants are the result of evolution in desert climates. They do not share any ancestors that have these desert adaptations.

When species develop similar adaptations in response to similar environments, it is a type of convergent evolution (described in Chapter 7). In this case, members of different plant groups became more similar over evolutionary time because they both lived in desert biomes. Euphorbia and cacti are called ecological equivalents because they fill the same ecological role in their separate ecological communities.

Anatomical, physiological, and behavioral adaptations help to maintain homeostasis in hot environments. For example, some mammalian ears have a high surface area. By exposing these to the breezes, animals like jackrabbits and elephants can shed heat to the surrounding air (Figure 11). The structure of the ears is a reflection of their function. At night, the ears could lose heat that the jackrabbit needs. The animal's circulator system controls the amount of blood flow into the ears to regulate heat loss. Behaviors such as holding the ears close to the body also help to retain heat.

https://en.wikipedia.org/wiki/Hare#/media/File:Jack_Rabbit_Ears.jpg

Figure 11. Jackrabbit (*Lepus*) ears can shed heat to the environment.

Compass plants (Figure 12) live on North American prairies where summers are hot. The tips of their leaves twist an a way that minimizes the surface that faces the midday sun, conserving water and giving the plant its name. This orientation reduces the amount of light energy that the plants collect, but water tends to be more limiting on the grasslands. Individual plants can respond to water stress by growing deeper roots. Compass plant roots can go 5 or more meters underground to collect water. A compass plant growing in a wetter environment may invest less energy in roots and use its resources for reproduction or other purposes.

https://en.wikipedia.org/wiki/Silphium_laciniatum#/media/File:Silphium_laciniatum_Arkansas.jpg

Figure 12. Compass plants (*Silphium laciniatum*) orient themselves to the sun. The position of their leaves conserves water.

**Perennial** plants like the compass plant are able to grow large because they live for multiple years. Perennial plants often protect their tissues with chemicals or physical structures that discourage predators. They invest in structures such as the large taproot of the compass plant. **Annual** plants quickly grow from seeds, produce their own seeds when they are still small, and die before winter. They tend not to invest in large root systems, instead putting their resources into reproduction.

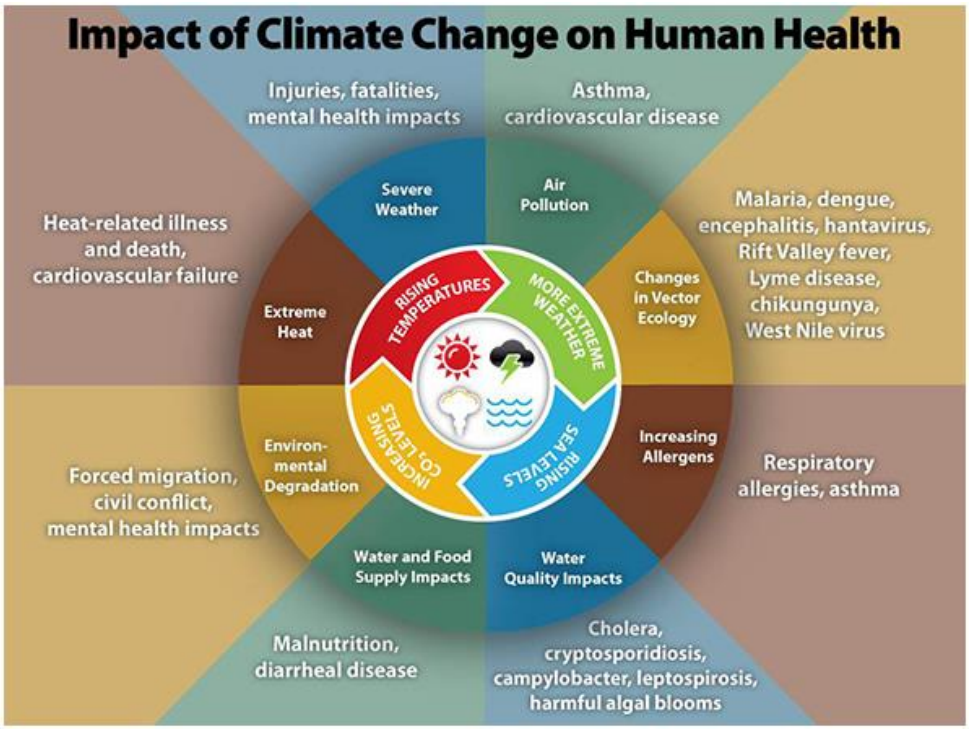
Natural selection tends to increases the frequency of alleles that are helpful in particular circumstances. When circumstances—such as climate—change, the same adaptations may reduce the fitness of an individual. To learn more about how climate change might influence human health through direct or indirect effects, see **Make the Medical Connection: Climate and Disease**

**Misconception Alert: Evolutionary adaptations are the result of trying**

**FALSE**. Evolutionary adaptations are not the result of trying to maintain homeostasis, but those that inherit useful adaptations—including the ability to make adjustments—usually leave more offspring. The mutations leading to those adaptations are random.

**Make the Medical Connection: Climate and Disease**

Changes in climate can influence human health in many ways (Figure 15). One way is by shifting the boundaries of life zones. As some areas become warmer and wetter, for example, they may provide habitat for parasites. As areas become drier, people may have to rely on less healthy water supplies.




http://www.cdc.gov/climateandhealth/effects/

Figure 13. The potential influence of global climate change on human health.

- Can the CDC predict the exact health impacts of a change in global climate?
- Would any changes in global health due to climate change influence all countries equally? Which would have greater consequences or more difficulty dealing with them?
- What steps should be taken at the global, national, or local level to prepare for any health crises caused by climate change?

**Check Your Understanding**

- What is the difference between an evolutionary adaptation and a physiological adaptation?
- What are some ways that animals respond to unfavorable temperatures?
- What are some ways that plants respond to harsh conditions?

## Adaptations May Involve Evolutionary Tradeoffs

Birds and mammals are **endothermic**, meaning that they produce most of their heat biochemically inside their bodies. Other animals are **ectothermic**, meaning that they get their heat from the environment. Being endothermic costs a lot more energy, but allows animals to be active in a variety of environmental temperatures. Some animals are occasionally endothermic. For example, some honeybees flap their wings rapidly within the hive on cold days and use the heat they generate to let them fly. The evolution of endothermy represents an **evolutionary tradeoff**. Being endothermic comes with the benefit of allowing animals to be active in areas or seasons that would otherwise be too cold. It comes with the cost of requiring the animals to eat much more food to power their heat production.

Photosynthesis strategies also demonstrate evolutionary trade-offs. Most plants use a method called C3. This type of photosynthesis leads to water loss in hot and dry conditions. The C4 strategy used by some plants, such as corn and crabgrass, allows plants to avoid water loss. C4 plants can keep their leaf pores closed more than C3 plants can. But C4 photosynthesis uses more energy than C3 photosynthesis. The tradeoff of decreased energy efficiency for increased water efficiency helps C4 plants to dominate climates close to the equator. C3 plants dominate in the higher latitudes. Desert plants use a variation called CAM photosynthesis. It allows the plants to keep their leaf pores closed during the day, but results in slow growth because the plants take in much less carbon dioxide.

### Check Your Understanding

- What is an evolutionary tradeoff?
- Describe the costs and benefits of either endothermy or C4 photosynthesis.

## Different Biomes Drive Different Adaptations

<u>Tropical Rainforests</u>

Tropical rainforest plants are adapted to heavy rainfall. Leaves may have “drip tips” to shed water, and usually have a rot-resistant coating because warm, wet climates promote bacterial growth (Figure 14). Plants can grow all year, so tropical trees do not have growth rings like temperate trees do.

https://en.wikipedia.org/wiki/List_of_ecoregions_in_North_America_(CEC)#/media/
File:Flickr_-_ggallice_-_Bromeliads.jpg

Figure 14. Bromeliad plants grow on a tree trunk. Their tips are waxy and pointed to allow rain to drain away. They trap dust at their bases to harvest nutrients from the air. They can also store water for when rainfall is low. Growing on tree trunks allows them to get above other plants that might block their light.

High levels of water and sunlight allow a lot of photosynthesis—high productivity. This leads to crowding and competition for sunlight. One way to compete is to grow above the competition. Rainforest trees can be very tall, up to 45 meters. Ecologists may need huge cranes or technical climbing equipment to study the rainforest canopy. As discussed in Chapter 7, Tropical soils tend to be leached of nutrients. Tropical rainforest plants have many different adaptations for the low soil nutrient levels, including absorbing nutrient particles in the air. The low nutrients and high productivity lead to many types of specializations and high plant diversity. Because there are so many plant species, there are many species of animals, fungi, and microbes. Many species are highly specialized. Diversity will be discussed more in Chapter 17.

## Deserts

Desert fungi are mostly found underground or as part of lichens on rocks. Desert plants often have waxy coatings that reduce water loss. The shiny surface of some leaves reflects sunlight. Shrubs have small leaves to conserve water. Other plants have no leaves at all and do photosynthesis on other surfaces (see Evolutionary Perspective: Ecological Equivalents), or do CAM photosynthesis, as discussed above. These adaptations result in less photosynthesis, so plants often invest in toxins or sharp spines, which protect them from grazing. They may also use chemicals to keep other plants from growing too close.

Precipitation comes in infrequent, heavy bursts, sometimes causing flash floods. Some cacti can take advantage of the rare, heavy rains by expanding to hold more water. Other plants store water in their roots. Some plants and fungi only reproduce after heavy rains, then die, leaving their seeds behind to wait years or decades for the next rain. Annual plants will sprout, produce seeds, and die, all in a year or less. This allows them to avoid both bad seasons and bad years. Some plants can go dormant for years until rains return (Figure 15).

https://en.wikipedia.org/wiki/Anastatica#/media/
File:Anastatica_hierochuntica.jpg

Figure 15. A species of resurrection plant that hides seeds inside an apparently dead plant during dry seasons, then “revives” when it gets enough water.

Desert animals can maintain thermal homeostasis using **behavioral thermoregulation**. As discussed in Chapter 6, microclimates can have very different temperatures. Animals often spend the day underground, then emerge at night when temperatures are cooler (Figure 16).

https://www.nps.gov/orpi/learn/nature/kangaroo-rat.htm

Figure 16. A kangaroo rat outside its burrow. Many desert animals stay underground during the day.

Desert animals also have adaptations to avoid drying out. The waterproof covering, closable air holes, and concentrated wastes of insects all contribute to their success. Reptiles are also waterproof and concentrate wastes. Mammals concentrate their urine and rarely sweat.

Animals living in the desert may have trouble finding enough food, due to the low plant productivity. The low density and variety of plants per unit area means a low number and diversity of animals per unit area. It also puts endothermic animals at a disadvantage due to their higher energy requirements.

## Temperate Rainforest Biome

Temperate rainforests have seasons of higher and lower temperatures. They rarely get below freezing, so they can grow all year. They have high rainfall for most of the year, though some seasons are wetter than others. The year-round growth can lead to crowding. Plants closer to the ground are adapted to growing in the shade. Other plants and fungi may grow on the sides of trees to get higher above the plant growth. The tallest and largest (by mass) trees in the world are **conifers** (cone-bearing trees) in temperate rainforests. Size allows them to avoid the shade of neighboring trees.

Temperate rainforest plants are resistant to rot when alive, but the warm wet conditions break down dead tissues quickly. Some plants grow on decomposing material such as “nurse logs” (Figure 17). Evergreen trees contain chemicals that can burn rapidly, so long dry seasons or droughts can lead to large fires. Some species of conifer have cones that only open after a fire when new space has opened up.

https://www.nps.gov/places/old-mine-tour-nurse-logs.htm

Figure 17. Plants growing on a nurse log.

## Grassland Biome

In grasslands, precipitation approximately equals evaporation. Water does not leach the nutrients below where plants can reach them. The high nutrient levels, adequate water, and long summer days lead to fairly high productivity. Many grasslands have been converted to agriculture to take advantage of this productivity (see Chapter 7).

Savannas are grasslands with scattered trees. The regions are usually too dry for tree growth except along rivers and streams. In some areas, hard soil below the surface prevents deep root

growth, even when there may be enough water. Drier regions have short-grass prairies. Tall-grass prairies grow in wetter areas. The grasses usually have deep roots to reach and store resources.

Narrow leaves reduce water loss. Water is conserved even more by letting the leaves and shoots shrivel during the winter while the rest of the plant stays alive. Fires are common, and help to get rid of plants that would compete with the grasses (Figure 18). The fire does not hurt the grasses, which have stored their resources in the roots.

https://www.nps.gov/articles/wildland-fire-in-tallgrass-prairie.htm

Figure 18. Grasses are adapted to fire. Dry tops provide fuel while their roots store resources. Competing species such as trees are often killed by fire.

Grasslands may contain many species of grasses and other non-woody plants. They support a fairly diverse population of animals, including large grazing animals and the predators that hunt them. Grasses are difficult to break down, so vertebrate grazers usually have large stomachs and helpful bacteria to break down the plant tissue. Large stomachs require large bodies (Figure 19). Some insects pollinate flowering plants, but the grass pollen is spread by the wind. Seeds might travel on the wind or be carried by animals.

https://en.wikipedia.org/wiki/Puna_grassland#/media/File:Vicu%C3%B1a_Vigogne_Lago_Chungar%C3%A0_4570m_Chile_Luca_Galuzzi_2006.jpg

Figure 19. Vicuna llamas (*Lama vicugna)* grazing on a grassland in Chile.

## Temperate Deciduous Forest Biome

Temperate **deciduous** forests have warm and cold seasons with some water surplus. Productivity can be high in the warmer months. The diverse plant community supports a diversity of animals. Large leaves trap sunlight, leaving the lower levels in the dark. Shade beneath trees can provide a moist environment for fungi and bacteria.

Deciduous plants usually lose their leaves in winter or dry seasons (Figure 20). This conserves water and may help to avoid snow and ice building up on branches and breaking them. The tradeoff is that it also limits the growing season for deciduous plants. They must do all their photosynthesis for the entire year when they have active leaves. When the leaves are gone or small in the spring, much more light can reach the lower levels where young trees, shrubs, and smaller plants grow.

http://commons.wikimedia.org/wiki/File:Cornus_sericea_winter.jpg

Figure 20. Red osier dogwood (*Cornus sericea*) in winter. The plant is deciduous and has dropped its leaves.

Bright fall colors are caused by the tree cutting supply lines to the leaves. As the green pigment chlorophyll breaks down, other colors become visible. Temperature and sunlight are both cues that start the color change. Some trees have an early color change that may signal animals that fruit is ripe. Fallen leaves provide a nutrient source for decomposers.

Birds and mammals in temperate forests can respond to the seasonal variation by remaining active and consuming more food to keep up with calorie demands. This is most common in large mammals, whose bodies hold a lot of heat and can carry a lot of fat. Smaller mammals may store food for winter use. Some species—especially birds—migrate to better climates. Other species go into a seasonal shutdown in protected areas such as dens (Figure 21). They may have a full hibernation, dropping their temperatures to freezing, or they may have a lighter torpor, with smaller drops in body temperature. Ectotherms may also find protected places and let their temperatures drop.

https://commons.wikimedia.org/wiki/File:Dormouse1.jpg

Figure 21. Dormouse (*Muscardinus avellanarius*) hibernating. The nest is underground and lined with insulating plant material.

## Boreal Forest Biome

The cold northern boreal forests are dominated by conifer trees. Most conifers are evergreens with needle-like or scale-like leaves (such as pine, fir, and hemlock). The thin, waxy needles and the thick bark prevent evaporation and conserve water. They can continue photosynthesis all year, but very little growth can occur when most water is frozen. Conifer forests can be dense, creating shade that provides habitat for fungi. Fungi may be an important source of protein for mammals.

The needles and the shapes of trees reduce the buildup of snow that could break tree branches. The branches also tend to be flexible so that they bend down when covered with snow, then spring back up when the snow falls off (Figure 22). The needles can do photosynthesis during the winter if liquid water is available. Evergreens shed their needles every two or three years, but they do not drop them all at once. The acidic soil created by the fallen needles can prevent competing plants from growing. The tree community may be dominated by one species.

https://forestryandland.gov.scot/blog/sitka-spruce

Figure 22. Sitka spruce (*Picea sitchensis*) covered in snow. The branches are flexible and will bend with the weight of the snow. This may allow the snow to slide off. After the snow falls or melts off, the branches will spring back up.

Some conifer forests are very dry during warmer months, making fires common and potentially so large that they destroy entire forests. Forests that are normally wet all year can burn rapidly during drought years. The chemicals in conifer needles make them burn easily.

As in temperate deciduous forests, some animals are active all winter, while others spend the winter hibernating or staying in shelters with stored food. Some species migrate to warmer climates. Animals that remain active in winter may change their colors (Figure 23).

**A**

http://www.fs.usda.gov/detail/mbr/learning/nature-science/?cid=stelprdb5155214

**B**

https://commons.wikimedia.org/wiki/Mustela_erminea#/media/File:Mustela.erminea.jpg

Figure 23. Ermine (*Mustela erminea*) in winter (**A**) and summer (**B**). The black-tipped tail may cause predators to focus on the wrong part of the ermine.

Tundra Biome

Tundra biomes are dry and cold for most of the year. Water is mostly available when snow is melting. The dominant plant species are mosses and lichens. There may be shrubs or stunted trees in patches. These plants are adapted to grow slowly in an environment where soil conditions are poor and the growing season is short. Plants grow close to the ground for protection from the wind (Figure 24). Leaves are small to conserve water. They may be dark and shaped and oriented to absorb sunlight. Hairs may insulate the plants, reduce evapotranspiration, or allow water to condense (see Chapter 5, Why it Matters: Harvesting Water).

https://commons.wikimedia.org/wiki/Category:Tundra#/media/
File:2013-07-14_12_22_45_Alpine_flowers_along_the_Wheeler_Peak_Summit_Trail_in_Great_Basin_National_Park.jpg

Figure 24. Tundra plants grow low to the ground to conserve resources and avoid the force and dehydration of wind. Flowers may grow higher up to attract pollinators.

Most of the plant and animal productivity in the tundra happens in a very short time during the long spring and summer days. Some animals migrate to the north during late spring and summer to take advantage of the burst of productivity. Swarms of newly hatched mosquitoes and black flies make life very difficult for large animals, including humans. As with other biomes with cold winters, some animals migrate south or hibernate during the colder months (Figure 25). Mammals tend to have thick fur, short limbs, and put on a thick fat layer before winter. Birds may have downy feathers and fat for insulation. When they are on the nest, they often have a bare patch or skin on the underside so that heat can transfer from their bodies to their eggs.

https://en.wikipedia.org/wiki/Bird_migration#/media/File:BrantaLeucopsisMigration.jpg

Figure 25. Barnacle geese (*Branta leucopsis*) migrate south to avoid arctic winters, then return to breed in high rocky areas of the tundra biome where predators are rare.

## Permanent Ice Biome

Air temperatures rarely exceed freezing in some high northern latitudes and high mountaintops. No plants grow in these regions. Some algae can grow on snow under the right conditions (Figure 26). The relatives of this algae are green. The red pigment keeps the intense sun from damaging chloroplasts. It also absorbs heat, which melts water for the algae's use in photosynthesis. The algae are dormant in winter as they are covered by snow. In spring they release mobile cells that use flagella to reach the surface of the snow.

https://www.antarctica.gov.au/about-antarctica/plants/snow-algae/

Figure 26. Snow algae and cyanobacteria are common in the summer on high altitude or polar snow.

The animals that live on ice have many of the adaptations of the tundra animals. On mountains, the plants at lower elevations provide most of the productivity. Animals may feed at lower elevations but live on or near glaciers. The productivity in polar areas is mostly due to phytoplankton, which do photosynthesis in the sea near or below the ice. Polar animals usually do not eat phytoplankton directly; they eat animals further up the food pyramid, such as fish or animals that eat fish (Figure 27).

https://en.wikipedia.org/wiki/Ad%C3%A9lie_penguin#/media/
File:Adelie_Penguins_on_iceberg.jpg

Figure 27. Adelie penguins (*Pygoscelis adeliae*) breed and spend time on permanent ice, but they feed in the ocean.

**Misconception Alert: Species are perfectly adapted to their habitats**

**FALSE.** There is no perfect adaptation. Helpful adaptations are likely to spread in a population, but habitats are constantly changing. These changes might make certain traits more or less beneficial than they were before. Evolutionary trade-offs may prevent some traits from spreading. Random mutation may not have resulted in the best "solutions" to the problems of a habitat.

**Check Your Understanding**

- Describe some adaptations organisms may have to extremes of temperature or moisture
- Compare the plant adaptations for two or more biomes

**Case Study Part 2: Life Changes with Elevation**

Before starting on your mountain adventure, you might have done some research on what to expect at different elevations. For example, suppose the climate graph for a location along your trip looked like Figure 28. When you analyze the climate graph you can see that rainfall is high all year. Some seasons get more rain than other seasons, but there is no dry season. The average monthly temperatures never get close to zero, so precipitation would fall as rain. What adaptations might you notice in the plants at this location? They would probably have many of the adaptations of tropical rainforest plants, even though this area is slightly drier and colder than the area by the river where your imaginary journey started.

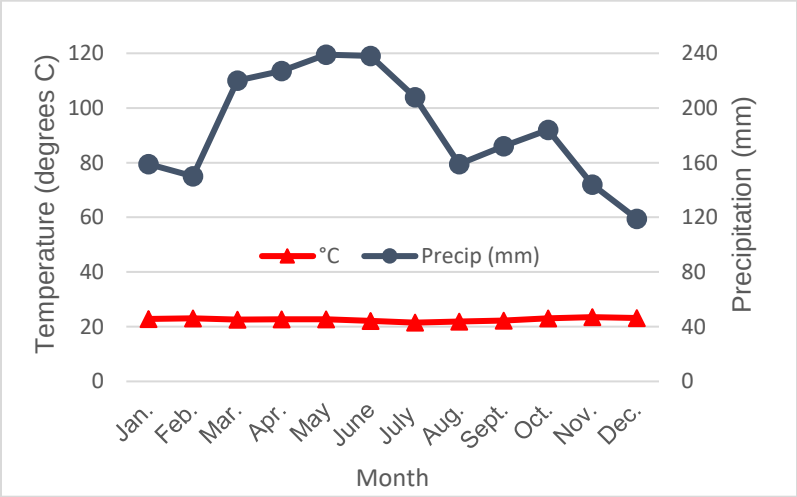



Figure 28. Climate graph for a location near sea level. The average total annual precipitation is 2219 mm. The average annual temperature is 22.7 ºC.

At higher elevations, you would start to notice gradual changes in the plant life. As you reached 2000 m, the climate graph might look like Figure 29.

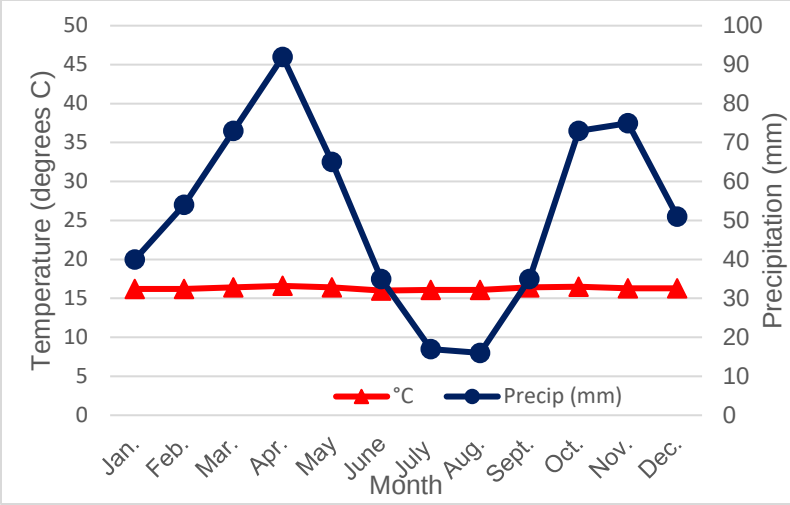



Figure 29. Climate graph for a location about 2000 m above sea level. The total annual precipitation is 626 mm. The average temperature is 16.3 ºC.

**Analyze the Figure**

- Does this area ever get below freezing? (Remember that these are averages.)
- Is there much seasonal variation in temperature?
- Is there a dry season?

Based on the climate graph, what sort of adaptations might you see in the plants at this elevation? How would they be different from the plants you saw below? How might the soil be different? Will the productivity of the area be the same as it was at the lower elevation? How does your prediction match the area shown in Figure 30? Could the season of the year influence what the photograph would look like?

https://upload.wikimedia.org/wikipedia/commons/2/2a/Paramo_de_Sumapaz_-_Yuri_Romero_Picon.jpg

Figure 30. Area at about 2200 m elevation with a climate like that in Figure 29.

A climate graph for an area 1300 m higher up might be very different (Figure 31).

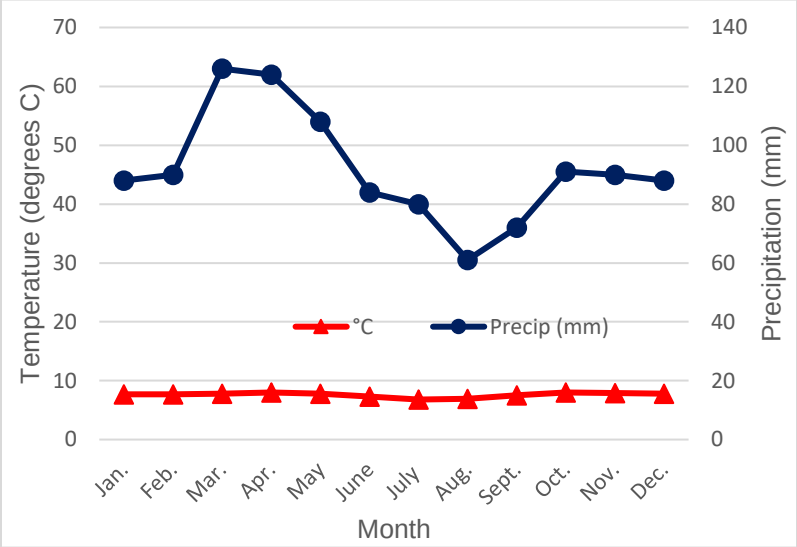



Figure 31. Climate graph for a location about 3500 m above sea level. The average annual precipitation is 1102 mm. The average temperature is 7.6 ºC.

**Analyze the Figure**

- Does this area ever get below freezing (recall that the temperature data is a monthly average for the entire day, averaged over 30 days, averaged over several years)?
- Is there much seasonal variation in temperature?
- Is there a dry season?

Based on the climate graph, what sort of adaptations might you see in the plants at this elevation? How would they be different from the plants you saw below? How might the soil be different? Does the plant life pictured in Figure 32 match what you expected to find in a location with this climate?

https://www.ncpedia.org/media/paramo-south-riobamba-ecuador

Figure 32. Area at about 3500 m elevation with a climate like that in Figure 31.

**Learning from the Case Study**

- Consider the global variation in life zones on land. How are increases in elevation similar to increases in latitude?
- What aspects of a climate are the best predictors of the adaptations that organisms will need in that zone?

# Key Concepts

- *Temperature, precipitation, and their variation determine biomes*
- *Climate and soil influence plant productivity*
- *Biomes lead to distinctive adaptations in organisms*
- *Adaptations allow organisms to maintain homeostasis. They may involve evolutionary tradeoffs*

# Apply the Concepts

**Learning Outcomes**

1. *Make and defend valid predictions about biomes based on climate information*
2. *Make and defend valid predictions about productivity and soil based on climate*
3. *Explain how climate and soil influence which species can live in an area*
4. *Explain how biomes shape the anatomical, physiological, and behavioral adaptations of organisms*

1. Refer to Figure 33.

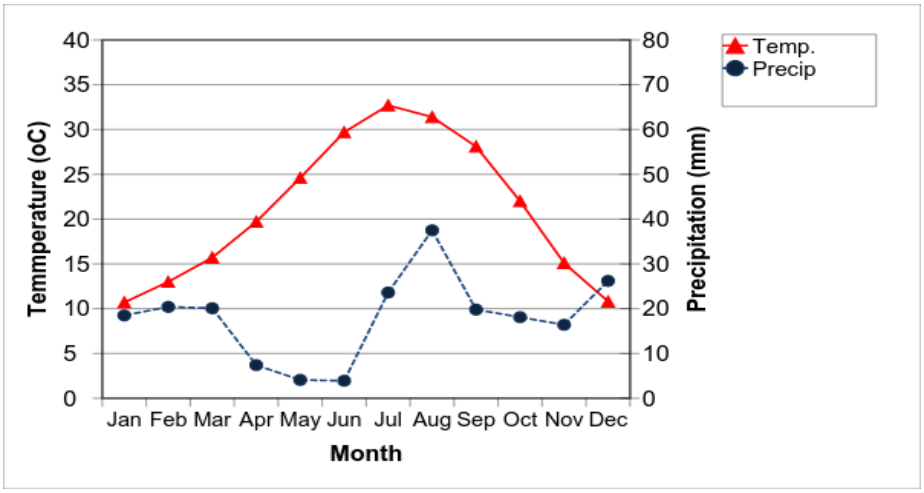



Figure 33. Climate graph for a location with an annual average temperature of 21.1 ºC and average total precipitation of 216.9 mm. It is about 780 m above sea level.

A. How would you classify the climate of this location?

B. Predict the general type of soil you would expect to find in this location and describe your reasoning.

C. Predict the general types of plants you would expect to find in this location and describe how the adaptations of those plants might increase their fitness in this location. *(Learning Outcomes 1-4)*

2. Refer to Table 5.

Table 5. Mean temperature and precipitation from Portland, OR.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 3.5 | 5.6 | 7.3 | 9.2 | 12.3 | 15.4 | 17.6 | 17.8 | 15.5 | 11.1 | 6.9 | 3.8 |
| mm | 176.8 | 143.5 | 129.8 | 94.9 | 77 | 60.8 | 20 | 32.5 | 61.7 | 117.2 | 194.5 | 208.6 |

A. Calculate the mean and median of the precipitation.
B. Explain why the mean and median are different.
C. Determine the standard deviation or standard error for the temperature.
D. Determine the biome of Portland, OR *(Learning Outcome 1)*

3. Refer to Figure 34.

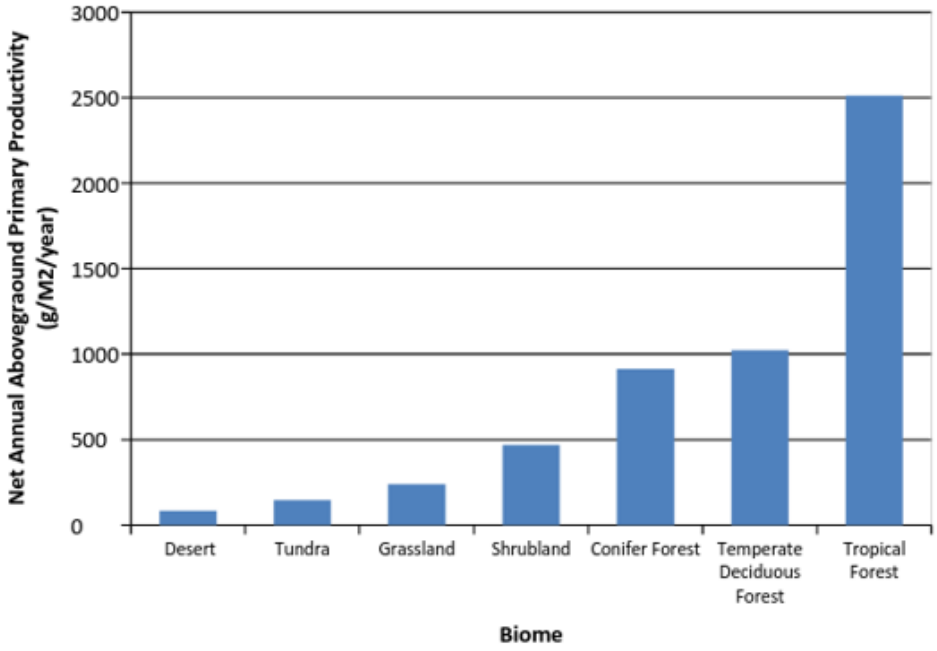



Figure 34. Net primary productivity in various biomes. The size of the biome will not influence the numbers in this graph because this is productivity per unit area. Places in the same biome will vary. Based on: Rosenzweig, M. L. (1968). Net primary productivity of terrestrial communities: prediction from climatological data. *American Naturalist*, 102: 67-74.

A. What is the main pattern that you observe?

B. Explain this pattern using the concepts in this chapter.

C. Would a biome be productive if it had high temperature but low precipitation *(Learning Outcomes 2 & 3)*

4. How might the mane of a male lion represent and evolutionary tradeoff between thermoregulation and breeding success? *(Learning Outcome 4)*

**Unit III: The Living World: Limits of Life**

# Chapter 9: Life Zones in Water: Regions and Adaptations

## Case Study Part 1: Giants with a Giant Impact

https://en.wikipedia.org/wiki/Sperm_whale#/media/
File:Mother_and_baby_sperm_whale.jpg

Figure 1. Sperm whale (*Physeter macrocephalus*) mother and calf. The mother may be 11 m long and weigh 14,000 kg. The calf's father may have been up to 16 m long and weighed 41,000 kg.

A sperm whale's size is impressive. It is the largest predator with teeth in the world. Blue whales are the largest animal that has ever lived on Earth. They have plates of baleen instead of teeth. Together, sperm whales and the many species of baleen whales are called great whales. The size of the great whales protects them from many predators, but orcas (also known as killer whales) cooperate in groups to kill these large whales.

Humans have been the greatest threat to whales for centuries. For about 1,000 years, humans hunted whales of all types for meat, oil, baleen, and other products. When small communities were hunting whales for their own needs, there was probably little impact on whale populations,

but commercial whaling became more advanced and effective, reducing whale populations to a tiny fraction of their pre-hunting numbers.

International whaling treaties and agreements have stopped almost all whale hunting. Most products harvested from whales can be produced more cheaply and easily from other sources. There is still a market for whale meat, so there is still a small amount of commercial whaling. Some communities with deep cultural histories of whaling are allowed to hunt whales for their own use. While hunting and other human activities are still a threat, most whale species have started to recover. Current research shows that great whales improve ocean ecosystems by bridging the zones, carrying needed nutrients.

**Learning from the case study:**

- What do great whales eat?
- How else might great whales influence their ecosystems?

# Learning Outcomes

1. *Accurately describe the conditions in different marine and freshwater life zones*
2. *Make and defend valid predictions about aquatic systems based on climate information*
3. *Make and defend valid predictions about productivity based on light and nutrients*
4. *Correctly explain how flow, temperature, salinity, and other factors influence adaptations of species*

**Vocabulary Toolkit**

**Roots**
Photo = Light
Phyto = Plant
Zoo = Animal
Oligo = few
Hypo = Low

**Opposites**
Euphotic and aphotic
Eutrophic and oligotrophic

**Word Watch List**
**Salinity**: Salt content of water
**Estuary**: Area where fresh and saltwater meet
**Photic zone**: Zone where light penetrates water
**Euphotic zone**: Zone where most light penetrates water
**Benthic zone**: Base of a body of water, such as a lake bottom or sea floor
**Aphotic zone**: Zone below where light can penetrate water
**Littoral zone**: Water zone near shore where vegetation can reach surface
**Intertidal zone**: Zone that is covered with water at higher tides and dry at lower tides
**Continental shelf**: Relatively shallow zone at edge of continent
**Phytoplankton**: Tiny floating producers
**Zooplankton**: Tiny floating animals
**Oligotrophic**: Having low nutrient input levels
**Eutrophic**: Having high nutrient input levels
**Hypoxic**: Containing low levels of dissolved oxygen
**Anoxic**: Containing no dissolved oxygen
**Point source pollution**: Pollution with identifiable origin
**Aquifer**: Groundwater location
**Hydrodynamic**: Describes a shape that reduces drag in water, especially at high speeds

**Most of Earth's Water is in Oceans**

About 98% of Earth's water is saltwater (Figure 2). **Salinity**—the amount of salt in the water—is one way to classify water. Saltwater has a salinity of about 3%, though it varies. In **estuaries** where freshwater meets saltwater, the water is described as brackish. This represents a tiny portion of the water on Earth, but it can be very important ecologically. Most of the fresh water on Earth is frozen in the ice caps and glaciers. Another large portion of the fresh water is underground.

The remaining freshwater is contained in lakes and ponds or flowing in rivers and streams. The Great Lakes of Canada and the United States hold about 20% of Earth's fresh water. Lakes have many forms, sizes, and depths. Not all lakes are freshwater. The Great Salt Lake and Mono Lake are saltwater lakes. They have no natural outlets. Water evaporates, leaving the salt and other minerals behind.

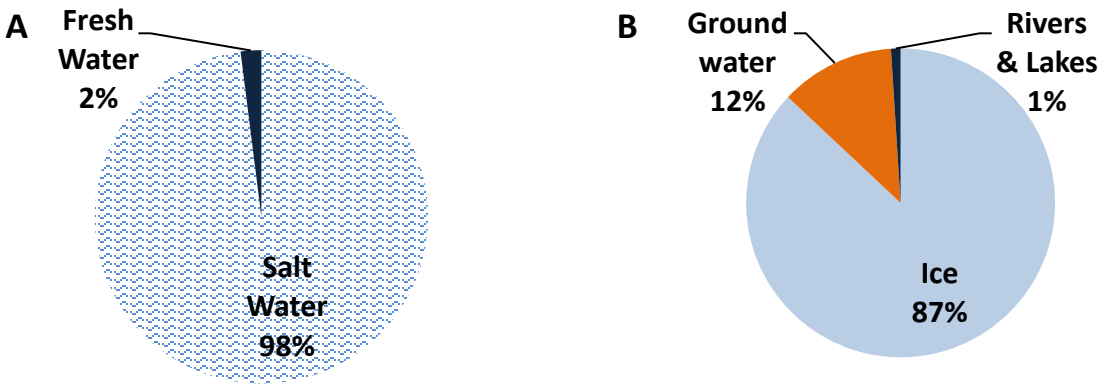



Figure 2. Distribution of Earth's water. **A**. All water. **B**. Fresh water only.

**Analyze the Figure**

- Where is most of Earth's water?
- How much of Earth's freshwater is in rivers, lakes, or streams?

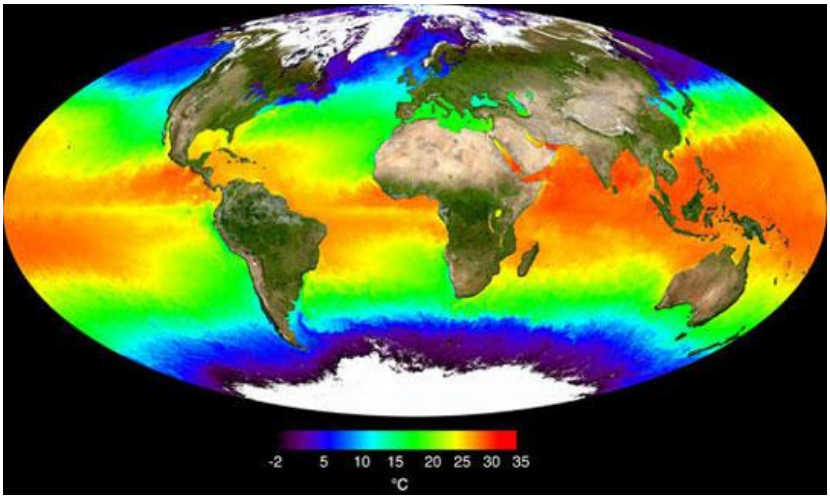
About 70% of Earth is covered by the saltwater sea. All the oceans are connected, but for convenience, different regions of the sea are called oceans (Figure 3). The Pacific Ocean is the largest. The word sea can also be used to describe large bodies of saltwater that are mostly or completely surrounded by land. The Mediterranean and Baltic Seas are examples of seas that are open to the Atlantic Ocean. The Dead and Caspian Seas are surrounded by land.

http://www.srh.noaa.gov/jetstream/ocean/ocean_intro.htm

Figure 3. Map of the sea, showing the oceans. While it is convenient to have different names for the oceans, they are all connected.

**Physical Characteristics Define Aquatic Life Zones**

Ocean temperatures vary according to their latitude (Figure 4). Because of water's high thermal inertia, the variation in temperature is much less than on land. Polar ocean temperatures are about -2 $^{o}$C (freezing temperature for seawater), while tropical oceans can reach 35 $^{o}$C. There may be seasonal temperature variation, but it is also less extreme than for air temperatures.



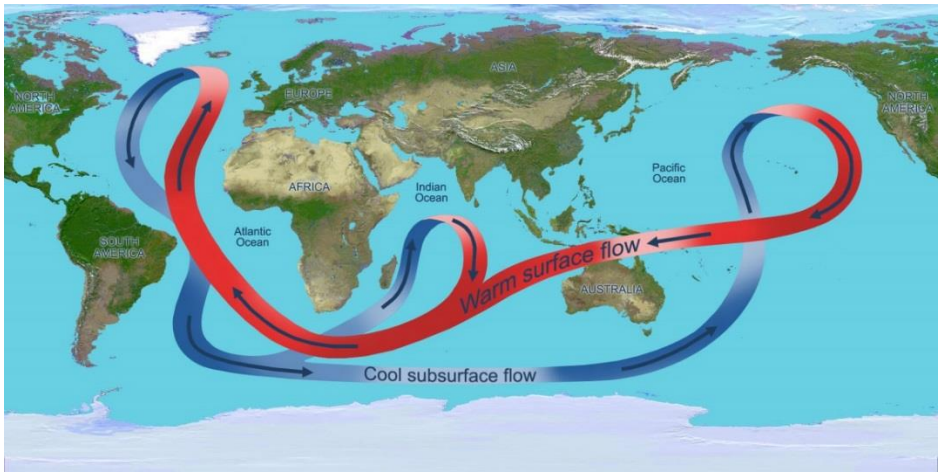

http://visibleearth.nasa.gov/view.php?id=55878

Figure 4. Worldwide ocean temperature.

**Analyze the Figure:**

- What is the water temperature near the equator?
- What is the general pattern of ocean water temperature?

Ocean currents distribute heat throughout the world and influence climates on land. The warm water from the equator flows to colder regions as the cold water from the Polar Regions flows to warmer areas (Figure 5). Warm currents bring warm, moist air to high latitude regions. When the air masses move over cooler land, they raise temperatures and release precipitation (see Chapter 6). When cold currents flow near hot regions, the cold, dry air masses cause more evaporation as they heat up. This creates extremely dry areas like the Skeleton Coast of southeastern Africa, which gets only about 10 mm of rain a year. Because cold water is denser than warm water, it sinks, while warmer water rises. These currents are not always in the same place, but they have a fairly predictable general pattern.



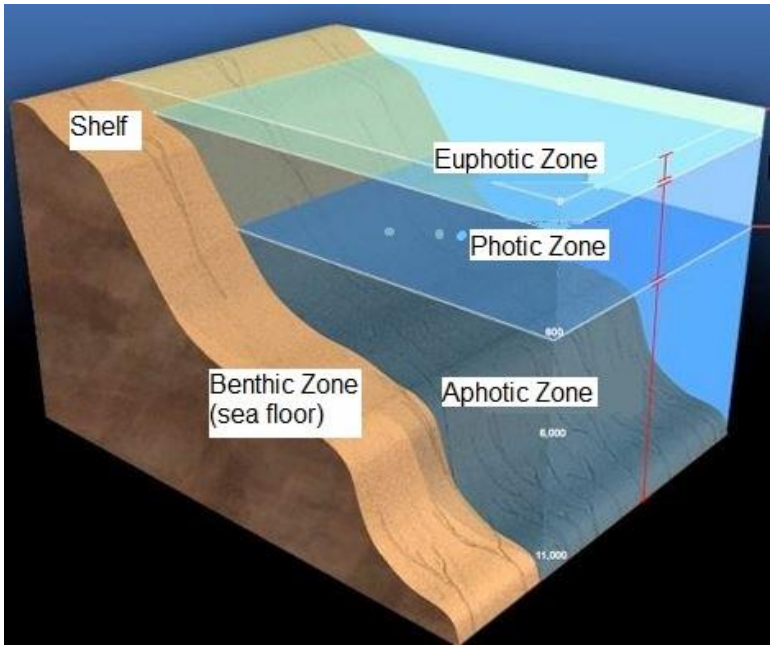

http://www.nasa.gov/images/content/435715main_atlantic20100325-full.jpg

Figure 5. Example of some major ocean currents. There are many other currents.

**Analyze the Figure**

- How does latitude influence the temperature of the currents?
- Which currents are near the surface?

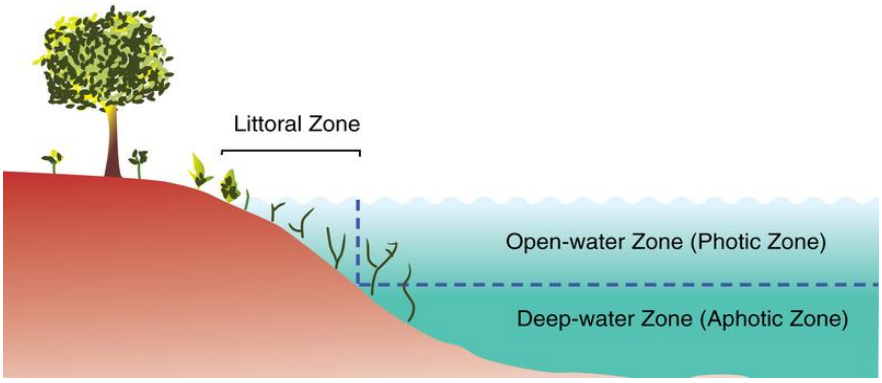
Aquatic habitats can be divided into different zones based on depth and light (Figure 6). Particles in the water absorb and scatter light. Longer wavelengths (reds and yellows) only penetrate about 100 m. Shorter wavelengths (blue and green) travel farther. This is one reason for the apparent color of water. The actual depths of the zones of light depend on the clarity of the water. Both abiotic factors (such as silt) and biotic factors (such as algae) influence water clarity. The **photic zone** is where visible light penetrates the water. The **euphotic zone** gets the most light. The **benthic zone** or sea floor starts at the edge of the water. The completely dark **aphotic** zone begins below about 400 m.




Adapted from: http://oceanexplorer.noaa.gov/edu/learning/3_deepsea_corals/activities/ocean_zones.html

Figure 6. Zones of light in the ocean. Scale is distorted to show detail. The benthos is the bottom of the water column no matter how shallow or deep the water is. Other systems for classifying the ocean may contain several more divisions. Lakes can also be divided this way.

The **littoral zone** is generally defined as the area near shore where vegetation is rooted in the benthos (Figure 7). The littoral zone is important habitat, especially for young fish hiding from large adults. While some of the productivity near the shoreline is due to plants, the productivity in the open-water zone is due to microscopic organisms.




http://commons.wikimedia.org/wiki/File:Primary_zones_of_a_lake.png

Figure 7. Potential zones in a lake. A shallow lake may have no aphotic zone, but it will still have a benthic zone at the bottom. The littoral zone is also called the shoreline. The open lake that receives light is the photic zone. Other classification systems may include more divisions.

Lake levels may vary between seasons and years, but local sea level changes daily due to the gravitational pull of the moon. During low tide, more of the land is exposed. If the shoreline is flat, large areas of land may be exposed. Areas that are covered with water during some stages of the tides, and dry in others, are called **intertidal zones** (Figure 8). The producers in these zones are usually multiple species of seaweed. Most of the animals are invertebrates that can hold onto surfaces that may be pounded by waves. These animals must find water during low tide or be able to resist drying out. The intertidal zone may have tide pools that trap water. It may have stretches of sand or small rocks that don't trap water, or it may be a steep face of rock or ice. Even if organisms stay underwater in tide pools, they will probably experience large changes in temperature. Some intertidal zones are subject to violent wave action most of the time. Others are calm except during storms.

**A**

https://en.wikipedia.org/wiki/Intertidal_zone#/media/File:Newport_beach.jpg

**B**

http://www.ozcoasts.gov.au/indicators/hermit_crabs.jsp

Figure 8. Intertidal zones in **A**. Newport, RI, USA and **B**. Queensland, Australia.

**Analyze the Figures**

- Compare the slope of the intertidal zones
- Compare the substrates of the intertidal zones
- What other differences or similarities do the photographs show?

**Check Your Understanding**

- Why would colder currents flow deeper than warm currents?
- How does life differ in the different depth zones of marine habitats?
- Explain why productivity is high in some marine zones, but low in others.

## Light and Nutrients Drive Aquatic Productivity

Primary productivity in aquatic systems depends on the availability of light and nutrients. In the ocean, beyond the intertidal zone, but where water is still relatively shallow, are the **continental shelves**. Here both light and nutrient levels are high, leading to high productivity. Runoff carries nutrients from the land. Ocean currents that hit the continent are also forced upward, causing upwelling (upward movement) of nutrients from deep in the ocean. The most highly productive marine habitats, kelp forests and coral reefs (Figure 9), are on continental shelves.

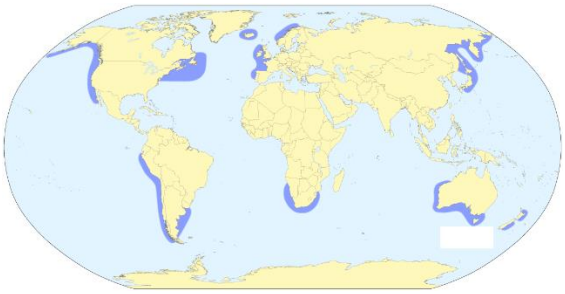
**A**

hhttps://oceanservice.noaa.gov/facts/kelp.html

**B**

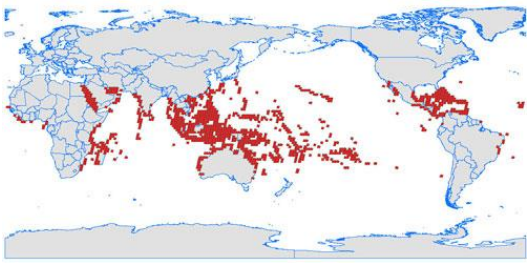
https://www.nps.gov/im/sfcn/coral-reefs.htm

**C**



Modified from: https://commons.wikimedia.org/wiki/File:Kelp_forest_distribution_map.png

**D**



http://www.nasa.gov/vision/earth/lookingatearth/coral_assessment.html

Figure 9. Highly productive areas on continental shelves. **A**. Kelp forest in California, USA. Kelp grows anchored in the benthos and extends up to the surface. **B**. Coral reef in Fiji. Coral are small colonial animals that secrete the hard material. They have a mutually beneficial relationship with algae that do photosynthesis. **C**. Worldwide distribution of kelp forests. **D**. Worldwide distribution of coral reefs.

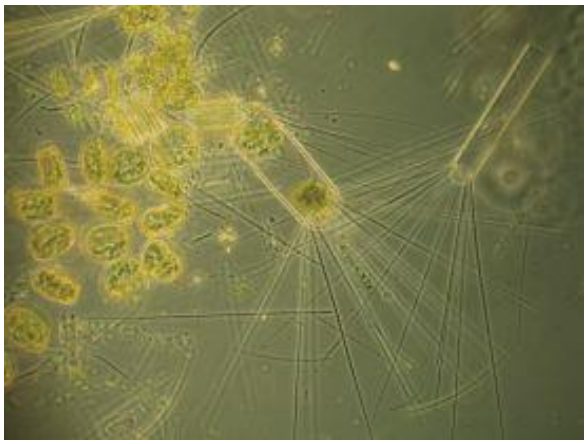
### Analyze the Figure

- Describe the different distribution of kelp and coral.
- Explain why their distributions are different.

Where the sea floor drops off beyond the continental shelf is the open ocean. Individuals tend to be clumped in areas of high productivity. They may also stay together as a protection from predators (this will be discussed more in Chapter 14). The amount of productivity *per unit volume* is very low in the open ocean because nutrients tend to fall to the sea floor, limiting productivity higher up. However, so much of the world is ocean, that most of Earth's *total* productivity happens here.

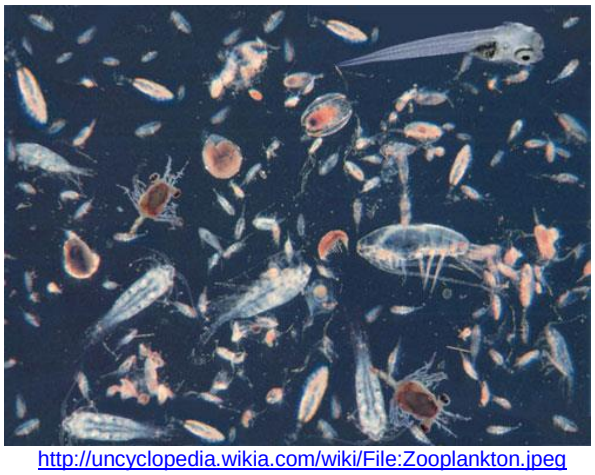
The producers are mostly microscopic **phytoplankton** (Figure 10 A), often one-celled protists called diatoms. Like the xenophyophores featured in Chapter 4, they have a hard outer covering. They move passively with water currents. The tiny floating animals that feed on them are called **zooplankton** (Figure 10 B).

**A**



http://www.antarctica.gov.au/about-antarctica/wildlife/microscopic-organisms

**B**



http://uncyclopedia.wikia.com/wiki/File:Zooplankton.jpeg

Figure 10. **A**. Phytoplankton from the Antarctic Ocean float near the surface to get light for photosynthesis. **B**. Zooplankton feed on phytoplankton and are consumed by larger animals.

The relationships between light, productivity, and oxygen are complex. Colder water can potentially contain more oxygen than warm water (Table 1). However, the actual amount of dissolved oxygen will depend on oxygen inputs (from photosynthesis and air near the surface) and oxygen consumption (from cellular respiration). If producers lack sufficient light to do photosynthesis, they will do cellular respiration. Most ocean organisms are ectothermic and their metabolic processes will happen faster at higher temperatures (within a reasonable range). This can increase the rate of both photosynthesis and cellular respiration.

Table 1. Relationship between water temperature and the solubility of oxygen (the maximum concentration of oxygen that can be dissolved in the water). Modified from: http://www.ecy.wa.gov/programs/wq/plants/management/joysmanual/dissolvedoxygen.html.

| Temperature (degrees C) | Oxygen Solubility (mg/L) |
|---|---|
| 0 | 14.6 |
| 5 | 12.8 |
| 10 | 11.3 |
| 15 | 10.2 |
| 20 | 9.2 |
| 25 | 8.6 |
| 100 boiling | 0 |

**Analyze the Table**

- Is the relationship between temperature and oxygen solubility constant? In other words, does each 5 $^{o}$C increase in temperature lead to the same reduction in oxygen solubility?
- A liter of water weighs 1000 grams. A milligram is 1/1000 of a gram. What percent of water is oxygen when it contains the maximum amount of dissolved oxygen?

Patterns of light, nutrients, oxygen, and biomass follow fairly predictable patterns as depth increases. (Figure 11; for help in reading graphs that show these patterns, see **Model Skill: Depth Profiles**). Light warms the upper layers of the water and provides energy to producers. If nutrients are available, this will increase their biomass. Consumers require producers and oxygen. Much of the producer biomass is consumed almost immediately. The consumers tend to stay out of the euphotic zone when they are not feeding because they are less visible to predators there. This movement pattern creates a higher level of biomass further down from the surface.

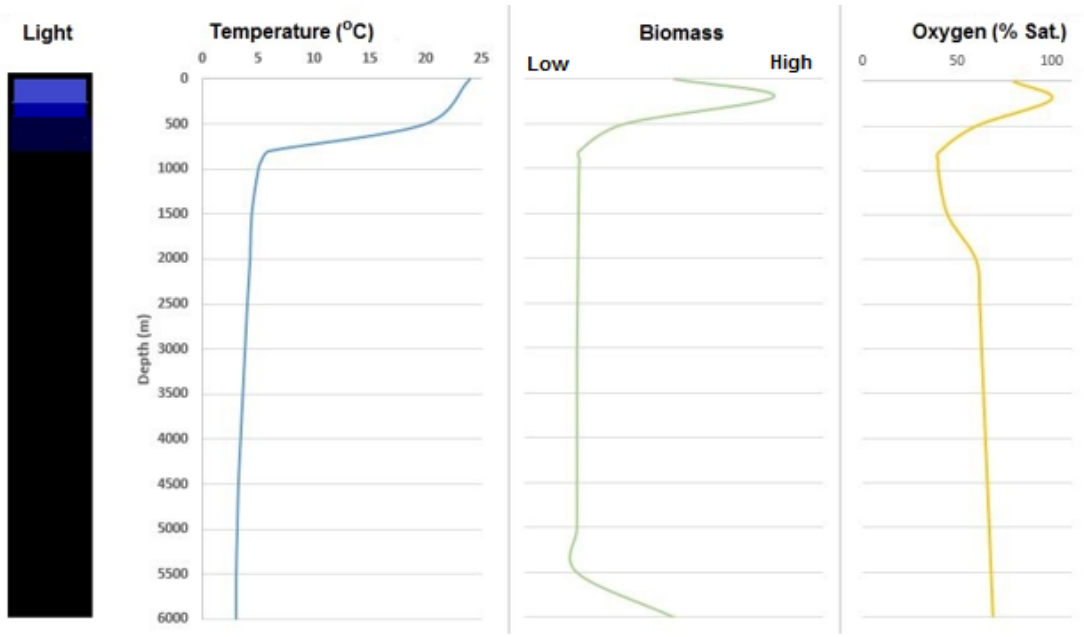



Figure 11. Temperature, biomass, oxygen saturation, and light trends in the ocean for an area 6000 m deep. Biomass is the mass of all living organisms. Patterns will vary according to climate, nutrients, and other factors.

**Analyze the Figure:**

- At what depth is biomass highest?
- Why would biomass and oxygen be high where light is high?
- Why is there an increase in biomass at the ocean floor?

Below the photic zone, photosynthesis is impossible. The food—living and dead—that supports the benthos comes primarily from above. Dead organisms and waste products that are not consumed on their way down support consumers in the aphotic zone. This results in a higher biomass in the benthos than in the depths directly above it, but still much lower than in the euphotic zone. There are also hot spots of productivity near the hydrothermal vents described in **Evolutionary Perspective: Hydrothermal Vents and the Origin of Life**.

**Model Skill: Depth Profiles**

Depth profiles are specialized line charts that show changes in variables as depth increases. On standard line charts the X-axis (horizontal axis) is the independent variable. In columns of water, soil, or atmosphere, depth would be the independent variable. However, in profile charts, depth is shown on the Y-axis (vertical axis). This represents the data as if the viewer could see the water, soil, or atmosphere column from the side. The two graphs in Figure 8 show the same data. The graph on the left (Figure 12 A) shows how it would look if the independent variable were on the X-axis. The graph on the left (Figure 12 B) shows the data as if the viewer were looking at the ocean in profile. Zero depth is the surface of the ocean. The amount of blue light transmitted declines to zero as depth increases. Neither of these graphs is inaccurate, but the graph style on the right is commonly used because it is more intuitive.

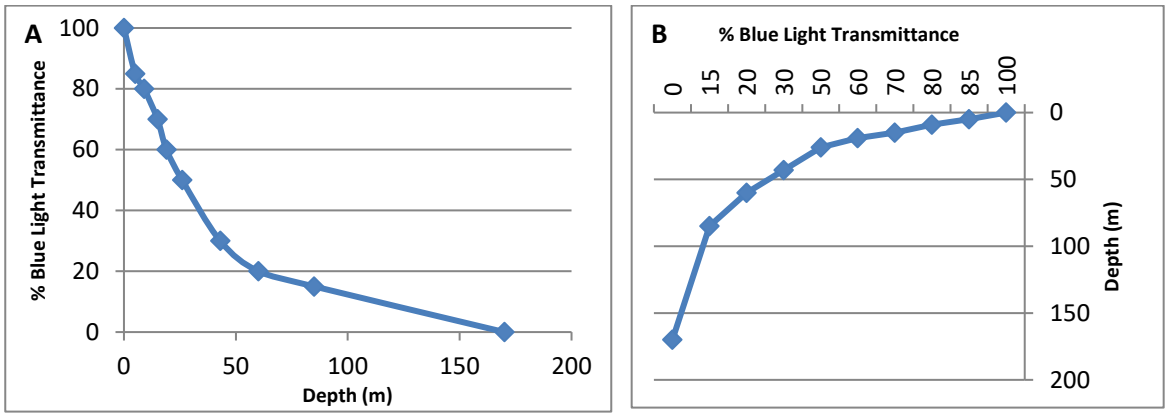
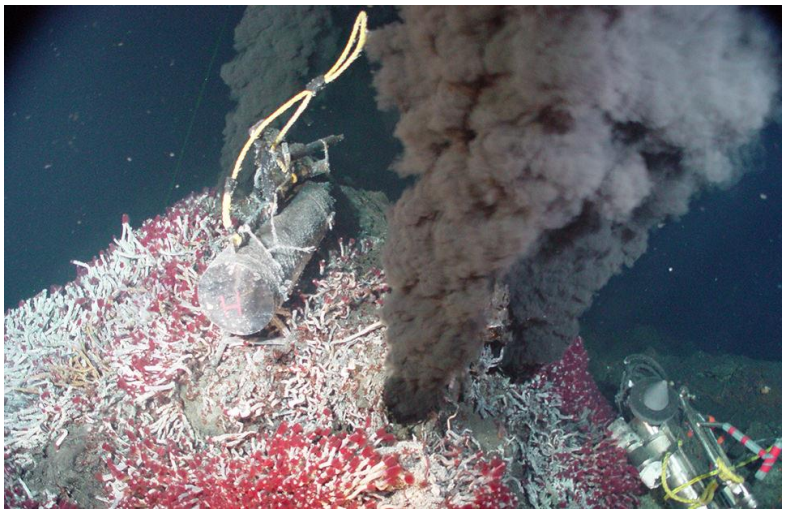



Figure 12. Two styles for depicting information on blue light transmittance in the ocean. **A** is the usual pattern with the independent variable on the X-axis. **B** is a depth profile, which is usually used in describing aquatic systems.

**Analyze the Figure:**

- What is the % blue light transmittance at 50 m?
- At what depth does the % blue light transmittance reach zero?

**Evolutionary Perspective: Hydrothermal Vents and the Origin of Life**



https://oceanservice.noaa.gov/facts/vents.html

Figure 13. Hydrothermal vents. The tube worms (white and red) have no digestive systems. They keep bacteria inside their bodies and survive on the sugar that the bacteria make.

Some of the most amazing ecosystems on Earth were not discovered until the late 1970s. Scientists looking for evidence of hydrothermal vents—super-heated water shooting out of the sea floor—found more than they expected. The pictures sent back by the first remotely operated vehicles showed large expanses of barren rock, then piles of clamshells near the vents. Researchers later found that these communities are unlike anything ever discovered. Instead of being powered by the sun, their energy base is hydrogen sulfide in the water that erupts from the vents. To us, hydrogen sulfide is toxic. To certain bacteria, it's like candy. All of the other members of the community depend on these bacteria, directly or indirectly.

Even more amazing, the bacteria give us clues about the origin of life. As you read in Chapter 4, all life needs energy. The energy can come from light or from large molecules that organisms eat or absorb. Hydrogen sulfide contains energy that the bacteria use to make sugar from carbon dioxide. This is like doing photosynthesis without needing light. The bacteria can then build more complex molecules from the nutrients in the vent water. Many scientists now suspect that the first cells may have started using a version of this process around three billion years ago.

The ratio of nutrient inputs to water volume is usually much greater in freshwater systems than in the ocean. Flowing water can pick up nutrients from sewage, agricultural fields, and many other sources. These nutrients support high productivity. Lakes with low levels of nutrient inputs are called **oligotrophic**. Lakes with high levels of nutrient inputs are called **eutrophic**.

The same processes that cause marine systems to become hypoxic or anoxic can be magnified by the high nutrient inputs in lakes. The oxygen depletion caused by algal blooms can kill fish and other aquatic animals. The dead animals add more nutrients to the water. Nutrients stay dissolved in the anoxic water, keeping nutrient levels high. This can cause thick mats of algae, followed by dead algae and fish rotting on the shore. Decomposers that break down the dead organisms consume oxygen when they do photosynthesis (Table 2). Some algal blooms are toxic causing more environmental and health issues. Where eutrophic water enters the ocean, it can cause “dead zones.”

Table 2. Comparison of eutrophic and oligotrophic lakes.

| **Eutrophic** | **Oligotrophic** |
|---|---|
| High nutrient inputs | Low nutrient inputs |
| High productivity | Low productivity |
| Lots of bacteria breaking down material | Little material to decompose |
| High oxygen consumption by bacteria | Little oxygen consumption by bacteria |
| Benthic zone has little or no oxygen | Oxygen throughout |
| Nutrients stay soluble | Nutrients buried |

Oligotrophic lakes are usually very clear and may have no aphotic level if they are shallow enough (Figure 14). Eutrophic lakes may be so full of algae that it is impossible to see more than a couple of centimeters down. Eutrophic lakes do not necessarily have high levels of nutrients in the water itself. Algae and other organisms may absorb nutrients as soon as they become available.

**A**

https://en.wikipedia.org/wiki/Littoral_zone#/media/File:Moon_Lake_shoreline_-_Riding_Mountain_National_Park.JPG

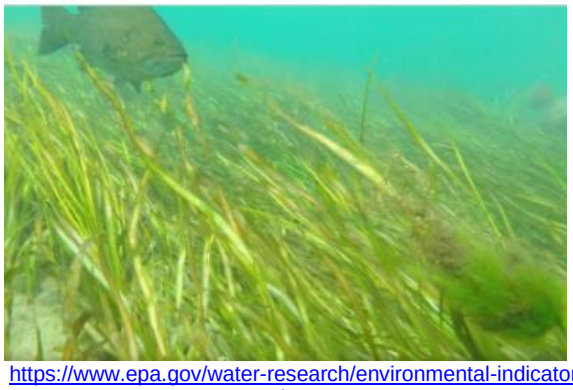
**B**

https://simple.wikipedia.org/wiki/Pond

**C**

https://www.usgs.gov/media/images/underwater-view-periphyton-rocks-and-lake-tahoe-shoreline-0

**D**



https://www.epa.gov/water-research/environmental-indicators-aquatic-surveys

Figure 14. **A**. Oligotrophic lake in Manitoba, Canada. **B**. Eutrophic pond **C**. Oligotrophic lake **D**. Eutrophic lake

**Analyze the Figures**

- Which lake type has more vegetation?
- Which water has higher clarity?
- How might nutrient levels explain your observations?

Lake temperatures in seasonal climates vary much more than ocean temperatures. Due to thermal inertia, temperature change will be less than that of the air, but it can still vary by season and time of day. Larger and deeper lakes will tend to vary less in temperature than small ones. The relationship between water temperature, density, and mixing causes seasonal anoxia in many lakes. For a more detailed discussion, see **Taking It Further: Thermal Stratification**. To learn about how nutrients and oxygen may influence fish harvests, see **Testing Hypotheses: Can balancing hypoxia and nutrients improve fisheries?**

**Taking It Further: Thermal Stratification**

Lakes in temperate climates can experience thermal stratification, or layering of water temperatures (Figure 15). In spring, water is still warming from the winter. Water is warmed from above, but the wind keeps water circulating throughout the levels. This keeps temperature fairly similar at all depths. Winds also help to add oxygen to the water from the air. Photosynthesis adds oxygen.

In the summer, the photic layer of the water warms. It is less dense than the water below it, so it does not mix with lower levels. This creates stratification with warmer strata or layers distinctly different from cooler ones. The place where the temperature changes sharply is the thermocline. Below the thermocline there is little oxygen input, and active organisms use up oxygen in cellular respiration. This can leave the lake bottom **anoxic**. Even at the surface, oxygen levels are lower in the summer than the spring or autumn because warm water holds less dissolved oxygen than cold water does.

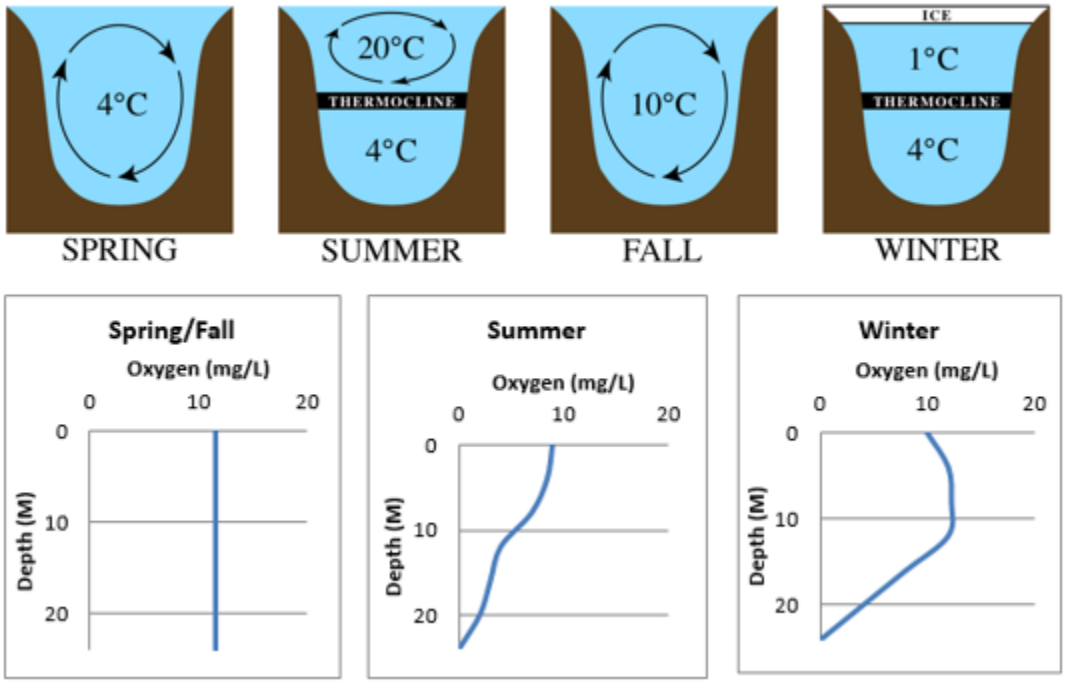



Figure 15. Stratification development and breakdown in a temperate lake. Upper diagrams show temperature trends. Lower diagrams show oxygen content. Actual values will vary by lake, but the general pattern is common.
Upper illustration from http://upload.wikimedia.org/wikipedia/commons/a/a8/LSE_Stratification.png

**Continued**

**Taking It Further: Thermal Stratification, cont.**

In autumn, there is much less heating of the surface and winds break up the layers. The mixing of surface waters with deep water makes the distribution of oxygen more uniform.

Recall that warm water is less dense than cold water and that ice is less dense than liquid water. Ice prevents oxygen in the air from being dissolved into the water. In cold winter climates, some photosynthesis may occur if the ice is not covered with snow and this can be an oxygen source. The bottom of the lake will have little or no oxygen because it is not receiving much, and because any organism doing cellular respiration will be using it up. Organisms that do photosynthesis in the light will do cellular respiration in the dark.

While these seasonal changes are critical to understanding lakes in temperate regions, alpine lakes fed by glaciers may stay cold throughout and never have thermal stratification. Shallow lakes may be warm all the way to the benthos. Tropical lakes will not experience seasonal temperature trends, though seasonal rainfall trends may influence them.

**Testing Hypotheses: Can balancing hypoxia and nutrients improve fisheries?**

If you were managing a coastal area for maximum fish catch, would you try to keep nutrient inputs high or low? High nutrient inputs tend to cause algal blooms. Algae without enough light exposure consume oxygen in cellular respiration. Bacteria that feed on dead algae also consume oxygen. Low oxygen levels (**hypoxia**) lead to decrease ability of fish to move, grow, and reproduce. Lack of oxygen (**anoxia**) kills fish. However, low nutrient levels mean low productivity. Most of the fish that humans eat are secondary or tertiary consumers. Primary productivity must be high to support large populations of fish at higher trophic levels. Malnourished fish have slower movement, growth, and reproduction. Starvation kills fish.

The research question (whether higher or lower nutrient levels are better for fisheries) is rather complex, so it may be helpful to look at 3 hypotheses.

Hypothesis 1: Low oxygen levels can be harmful to fisheries.

Hypothesis 2: Low nutrient levels can be harmful to fisheries.

Hypothesis 3: Effect of nutrient enrichment on fisheries depends on whether fish can effectively avoid low oxygen zones.

Oxygen levels usually vary with depth. At the surface, oxygen enters water by diffusion. Waves increase oxygenation of the water. Photosynthesis in the photic zone adds oxygen during the day. Further down, consumers and producers that are out of the photic zone use up oxygen. If there is little mixing of water between the layers, the bottom of the water column may be hypoxic (low oxygen) or anoxic (no oxygen).

Oxygen levels also vary by season due to local patterns of wind and sunlight. Recall that cold water holds more oxygen than warm water, but ice may block oxygen from entering water. Biological activity that either adds or depletes oxygen may also vary by season due to temperature-dependent metabolic rates or seasonal changes in behavior or population size.

Fish may face trade-offs between oxygen, food availability, and danger from predators. Fish do not usually stay in hypoxic or anoxic zones waiting to suffocate. They swim to areas with more oxygen (Figure 16). Prey fish will probably be threatened by more predators where oxygen is high. Both predator and prey may can swim quickly when their muscles have plenty of oxygen. The higher light at the surface might benefit predators that hunt by sight, but also allow prey to see predators.

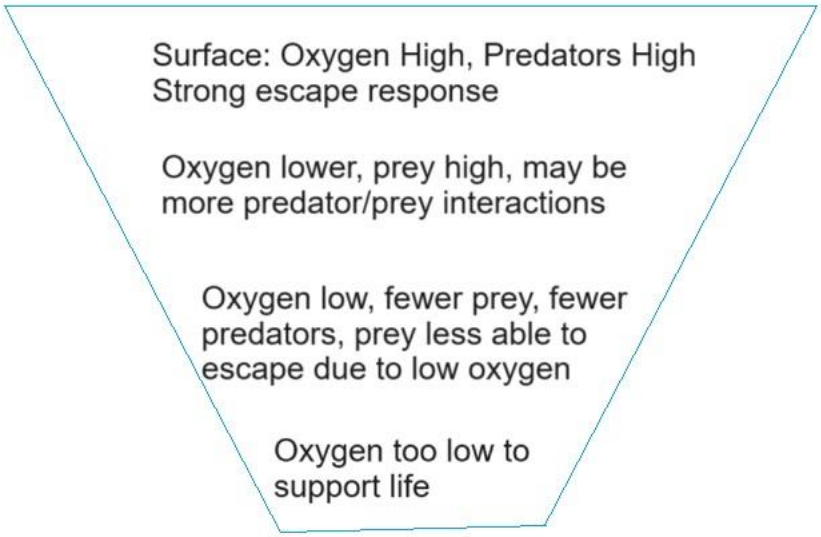



Figure 16. Effect of depth and oxygen on behavior and density of animals. The pycnocline is the level where the density of water increases rapidly due to cooler temperature. There is little oxygen mixing below this layer. Based on: Breitburg, D. (2002). Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries*, *25*(4), 767-781.

**Analyze the Figure**

- Describe some effects that oxygen level can have on predators and prey.
- Why would escape responses be weakened in the hypoxic layer?
- Do fish seem to be selecting high oxygen areas? Identify the evidence that led to your answer.

Estuaries and coastal waters that are partially enclosed by land usually have much higher nutrient loads than the open ocean. Water in nutrient-rich areas can often become anoxic or hypoxic. Breitburg (2009) found that in three locations (Chesapeake Bay in the southeastern US, Long Island Sound in the northeastern US, and Kattegat in Denmark) higher oxygen levels

in the bottom layer generally led to higher numbers of fish species in the area. Several other studies have found higher fish catches in places where oxygen is high. For example, the total number of commercial fish and invertebrate species caught in Hempstead Harbor of Long Island Sound (northeastern US) was higher when oxygen level was higher (Table 3).

Table 3. Catch of commercial fish, squid, and lobster. Reported in: Breitburg, D. (2002). Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries*, *25*(4), 767-781.

| Dissolved Oxygen (mg/l) | Harvest (Mean Number per Effort) |
|---|---|
| 4 | 400 |
| 2 | 30 |
| 0.5 | 5 |

Anoxic and hypoxic areas shrink the usable habitat for fish and other aquatic animals. Large portions may be lethal during all or part of the year. Eggs are vulnerable to falling oxygen levels because they are unable to move. Juvenile fish may sense the falling oxygen but be too small and weak to move effectively. Adult fish would usually not spawn in hypoxic regions, but the oxygen can drop after the eggs are laid and fertilized. Eggs can also fall into lower oxygen zones. Prey fish—including some juvenile fish that will grow to be predators—may stay out of hypoxic zones. The behavioral and physiological adaptations that fish make to deal with hypoxia tend to use energy that can't be used for growth and reproduction.

While anoxia and hypoxia are negative by themselves, the nutrient enrichment that causes them can be beneficial to fisheries by increasing primary productivity. If fish can move freely, and times of hypoxia and anoxia are short or predictable, fish can benefit from higher productivity in some areas, while avoiding danger from low oxygen. Long-term harvest and oxygen data from 14 European seas showed that the relationship between hypoxia and harvest was complex (Table 4).

Table 4. Catch of commercial fish in 14 European seas, averaged over several years. Summarized after: Breitburg, D. (2002). Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries*, *25*(4), 767-781.

| Hypoxia Pattern | Range of Harvests (Min. to Max) |
|---|---|
| Rare/None | Very Low to Moderate |
| Occasional/not widespread | Low to High |
| Seasonal/Widespread | Very Low to Very High |
| Year-Round/Anoxic Benthos | Very Low to Moderate. |

**Analyze the Table**

- Where were the highest maximum harvests?
- Where was variability in harvests highest?
- Which hypotheses are supported or refuted by these data?

Other factors can also influence fisheries, such as introduced species, pollution, disturbance of the sea floor, and toxic algal blooms. If anoxia occurs along with another stressor, it could be more damaging to a fishery.

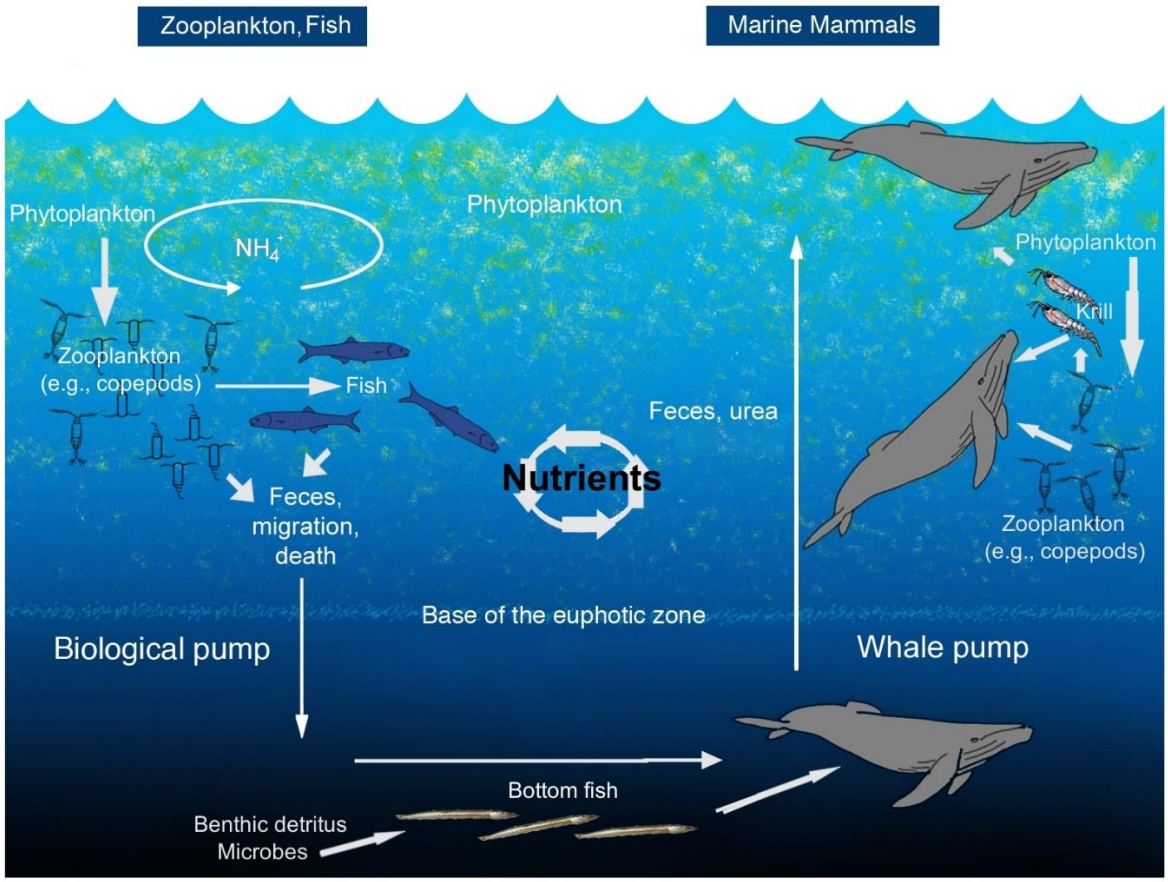
**Evaluate the hypotheses**

- Which hypotheses were supported by the data?
- Which hypotheses were supported by the data?
- What data would you gather next to help you understand the influence of oxygen levels on productive fisheries?

**Case Study Part 2: Whales Lift Nutrients**

Productivity in the open ocean is low because the producers in the photic zone have light, water, and $CO_2$, but not the nutrients they need. If nutrients can be moved into the photic zone, productivity usually increases. Whales can act as nutrient elevators. They feed on deep-level prey, then urinate and defecate in the photic zone when they surface to breathe (Figure 17). Their feces float. This “fertilizes” the euphotic zone with nutrients. The diving and surfacing of the whales can also help to mix nutrients through the depths.

Whales may live longer than a century. When they die, they sink to the benthos. Smaller dead animals are probably consumed long before they sink that far. A whale carcass has a dramatic influence on the food desert of the benthos. Invertebrates, fish, and microbes arrive in large numbers to feed on the dead flesh and on other animals attracted by the carcass.




https://commons.wikimedia.org/wiki/File:WhalePump.jpg

Figure 17. How organisms influence nutrient concentration in different marine zones. Whales tend to defecate at higher zones than they feed. The nitrogen whale feces contains is vital for making proteins, DNA, and other biomolecules. Iron is another critical nutrient that whale feces can add to an environment. $NH_4$- is ammonium from the waste of organisms.

Many species of whale move nutrients around the globe. They have feeding grounds in high-productivity areas like the Arctic and Antarctic, and breeding grounds in lower-productivity areas in the lower latitudes. Some do not eat at all in their breeding grounds, but they urinate, defecate, and sometimes die in the breeding areas.

**Learning from the Case Study:**

- Describe how depth of the ocean influences productivity and how the activities of great whales might increase productivity.
- Why might whales and other marine mammals have different effects on an ecosystem than fish have?

**Check Your Understanding**

- How does light influence temperature and oxygen?
- How do high nutrient levels result in low oxygen levels?
- How do climate and depth influence aquatic systems?

## Water Flows in Rivers and Streams

Flowing water creates a very different habitat than non-flowing water. The flow itself requires most organisms to have some way of avoiding being swept downstream. Plants may have stronger or longer roots. Algae can stick to rocks and other objects. Some animals anchor themselves, swim, or walk on the bottom of the channel. Bacteria collect in areas where the flow is slower. Rivers and streams tend to have more oxygen than lakes because oxygen is mixed into the water by waves and because shallow water has more surface area for oxygen to enter. Flowing water is often cooler as well if it is flowing from higher elevation areas, snow melt, or underground springs, allowing more oxygen to dissolve in the water.

Water flow or current depends on many factors including the volume of the water, how steep the course of the river is, and the width of the channel. When the channel narrows, the current will be faster because the same amount of water is flowing through a smaller channel. Current can vary greatly by season, day, and position in the river or stream.

Rivers in different biomes have very different characteristics. River temperature is dependent on climate, even though it will vary less than air temperature. Some rivers will be frozen for months of the year, while others will never freeze. A river or stream may vary widely in size, even drying up at times (Figure 18). All rivers vary in their volume, but rivers in temperate regions tend to have a more consistent flow than rivers in dry areas.

**A**

https://en.wikipedia.org/wiki/River#/media/File:Loboc_river.png

**B**

https://www.usgs.gov/media/images/green-river-near-colrain-massachusetts

Figure 18. **A**. The Loboc River in the Philippines. **B**. The Geen River in Massachusetts, USA.

**Analyze the Figure**

- How are the two rivers alike and different?
- Explain why different biomes would have rivers with different characteristics.

Any river can flood. Dry regions often receive little rainfall for long periods, then have severe storms. Rivers may be dry channels for months or years, then turn into large, destructive flows with little warning other than rain in the distance (see **Why It Matters: Flash floods**). The problem is increased where concrete channels have replaced natural riverbeds to conserve and control water. Water cannot seep into the ground, so all of it continues roaring downstream. Rivers fed by mountain snow will have large flow increases with the spring thaw. Monsoon seasons cause seasonal flooding in many parts of the world. The faster water flows, the more force it has to carry material with it. As water speeds up, it carries larger objects, and as it slows down, it deposits them (See Chapter 7). Deposition of silt and nutrients has created the fertile flood plains of the world, which are important agricultural areas.

**Why It Matters: Flash Floods Kill**

Flash floods can be deadly, especially in arid climates. Powerful storms can suddenly send large volumes of water down dry washes. People can be taken by surprise by a wall of water. Some people are swept away when they attempt to cross water in a road (Figure 19).

https://commons.wikimedia.org/wiki/File:Swift_rescue_assisting_a_trapped_woman_on_a_car_roof_during_flash_flooding_in_Toowoomba.jpg

Figure 19. Flash Flood rescue in Toowoomba, Australia. Moving water can easily carry away cars and trucks when it is only about 60 cm (2 feet) deep.

- Should concrete river channels be removed?
- In Arizona, the “Stupid Motorist Law” allows drivers who enter a marked flooded roadway to be billed for the cost of any rescue. Is this a fair policy?

As water flows, it can pick up a variety of pollutants, which end up in rivers and downstream in lakes and the sea. Factories producing pollutants are a form of **point source pollution** because it is easy to pinpoint the source. Nonpoint source pollution comes from places such as lawns, parking lots, buildings, and streets. You can attempt to identify non-point sources of pollution in your own community using **Do Try This at Home: Test for sewage contamination in rivers & streams**.

**Do Try This at Home: Test for Sewage Contamination**

Are any of your local rivers or streams contaminated with household sewage? Since the contamination can happen underground, it may not be obvious. Household sewage usually contains detergent from washing machines. The detergent often contains optical brighteners that glow under UV ("black") light. Ordinary tampons can be used as optical brightener monitoring traps (OBM traps). If there are optical brighteners in the water, tampons anchored in flowing water for a few days will absorb OBs and glow under UV light.

Use OBM traps to test for sewage contamination in a local waterway. Be sure to get appropriate permission. The tampons can be attached to stakes or other anchors with monofilament (fishing) line. Make sure they are secure. You are more likely to detect contamination when the water is not diluted by runoff from storms. Borrow a UV light to test the OBM traps. You will need a box or very dark room. To find the source of contamination, you can go back upstream and test points where water enters the stream or river.

For more information on the development of this technique, see http://www.scientificamerican.com/article/glowing-tampons-highlight-sewer-pollution/.

**Misconception Alert: Most water pollution comes from factories**

**FALSE.** Historically, every kind of waste has been dumped into nearby water. As nations have learned the importance of clean water, most have created and enforced regulations to protect water. Point sources are relatively easy to monitor and regulate. It is much more difficult to detect and control nonpoint source pollutants.

**Check Your Understanding**

- What factors influence the flow of a river?
- How does climate create more or fewer floods in a region?
- Compare the habitats of rivers and streams with those of lakes and ponds.

**Wetlands are Critical Habitat**

Swamps, fens, bogs, marshes, and similar areas are wetlands. They have standing water that influences soil in characteristic ways. They are generally so shallow that plants grow throughout them (Figure 20). They may be dry during some seasons or years.

**A**

https://en.wikipedia.org/wiki/Wetland#/media/
File:Laguna01.jpg

**B**

https://commons.wikimedia.org/wiki/
File:Peat_bog_between_Beinn_Odhar_and_Meall_Buidhe_-_geograph.org.uk_-_158415.jpg (cropped)

Figure 20. Wetlands. **A**. A marsh in Argentina and **B**. A peat bog in Scotland.

**Analyze the Figure**

- How are the two wetlands alike and different?
- Predict how some other wetlands might be different than either of the ones pictured.

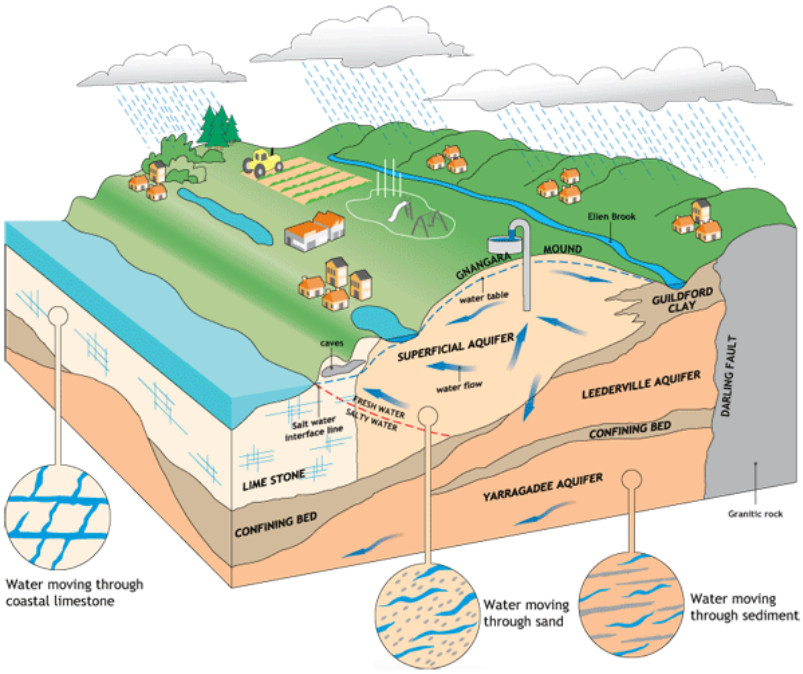
Wetlands do not account for much of the surface water in the world, but they are very important. Wetlands are critical habitat for many species of fish, bird, insects, and crustaceans (such as crabs). Wetlands often have high levels of nutrients, resulting in high productivity and food resources. The vegetation provides cover for hiding from predators. Wetlands also help to clean water because plants and algae remove excess nutrients and some toxins. Wetlands can reduce flood risk by acting as giant sponges, absorbing excess water that evaporates or is absorbed rather than flowing directly downstream. Many of Earth's wetlands have been drained to allow development. The United States and other countries have passed legislation to slow the loss of wetlands.

**Check Your Understanding**

- What are some major benefits of wetlands?
- Why do you think wetlands have been so heavily developed?

**Aquifers Contain Water Underground**

Recall from Chapter 7 that water can infiltrate the soil to become groundwater. About 12% of Earth's freshwater is underground in **aquifers** (Figure 21). As water flows down through layers of soil, it eventually reaches barriers that stop it. The water pools above the impermeable rock or clay, forming aquifers. These are rarely underground lakes (which would be prone to collapse). They are areas where water fills spaces between rock, gravel, and other material. Wells tap into aquifers. Wells are the major source of water for household use and agriculture in many areas. Groundwater may still be available even during severe droughts. If water is drawn out at a faster rate than it enters, aquifers are depleted, and can go dry. Drawing down aquifers can also cause land to sink.




http://www.water.wa.gov.au/sites/gss/ggs.html

Figure 21. Water can flow below the ground to form aquifers. This system of aquifers is in Perth, Australia.

**Analyze the Figure**

- How does water enter the aquifer?
- Describe some ways water might leave the aquifer.
- How might an aquifer get contaminated?

Another threat to aquifers is contamination from toxins. The toxins might come from leaking underground storage tanks, landfills that do not have intact liners, agricultural activities, and fossil fuel harvesting. The level of danger of any of these activities is the subject of much debate. Naturally occurring radiation and salt water can also contaminate aquifers.

There is usually very little biological activity in the aquifers themselves. They are in permanent darkness and not many nutrients usually enter the aquifer. The groundwater can reach the surface in springs, however, providing surface water for many species.

**Check Your Understanding**

- Describe some benefits of aquifers.
- Explain potential risks to aquifers.

## Aquatic Organisms Have Diverse Adaptations

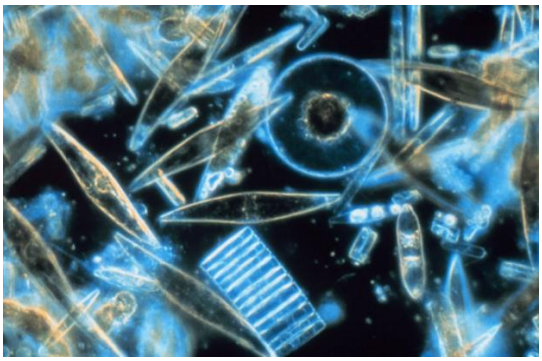
Life originated in the sea. Many species have spent their entire evolutionary histories in the sea. Others are descended from species whose ancestors left the sea for land or fresh water. These organisms may have very different ways of maintaining homeostasis in aquatic environments. (For more on homeostasis, see Chapter 8.)

Many marine species are in salt balance with the surrounding water, meaning that their internal concentration of dissolved salts and other molecules in is very similar to the concentration of the surrounding water. Many marine invertebrates, including sea stars (Figure 22) do not seem to regulate their internal salt concentration.

https://en.wikipedia.org/wiki/Starfish#/media/
File:Royal_starfish_(Astropecten_articulatus)_on_the_beach.jpg

Figure 22. Sea stars like this royal starfish (*Astropecten articulatus*) do not actively regulate their salt balance.

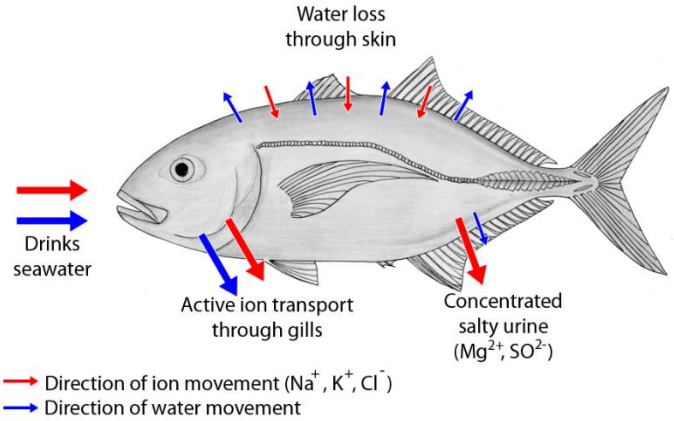
Other species regulate their internal concentration and type of salts and similar molecules. For example, seaweed produces materials that help to keep excess salt out. Many marine organisms can control their salt balance across their cell membranes. Unicellular diatoms do this (Figure 23). They also use exchange of salts and minerals to control their density, which allows them to float.



https://en.wikipedia.org/wiki/Pennales#/media/
File:Diatoms_through_the_microscope.jpg

Figure 23. Diatoms are microscopic organisms. They actively control their salt balance across their membranes. They have “tests” or shells that are made using some of the salts in the water.

Marine vertebrates get water from their diet or drink sea water (Figure 24). Recall from Chapter 4 that water is also a waste product of cellular respiration. Most marine fish can get rid of excess salt through their gills, kidneys, or both. Sharks and their relatives have a special gland in their digestive system to excrete extra salt. They do not drink sea water; they just absorb it over their gills. They don’t absorb a lot of excess salt because they manage the levels of dissolved material in their tissues.

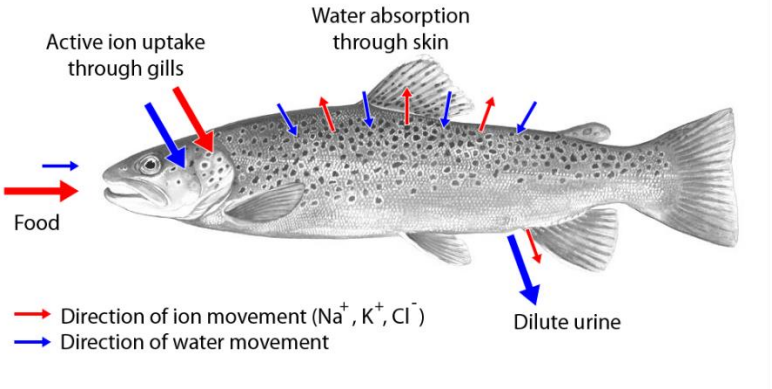



https://en.wikipedia.org/wiki/Osmoregulation#/media/
File:Osmoseragulation_Carangoides_bartholomaei_bw_en2.png

Figure 24. Salt and water regulation by marine fish.

Some sea birds and reptiles have special glands that allow them to get rid of excess salt. Marine mammals have adaptations allowing their kidneys to excrete high levels of salt in urine. Some species limit their salt intake by eating prey with lower salt content.

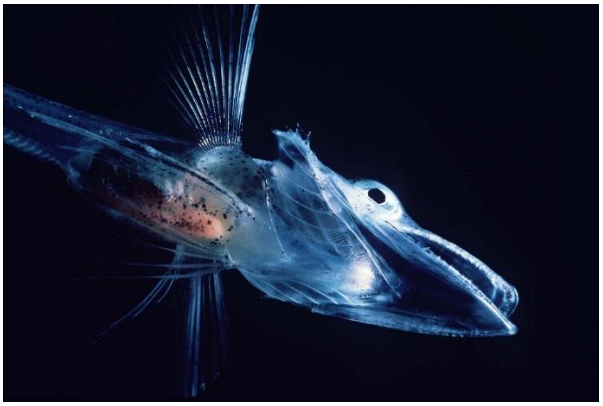
Freshwater species tend to take on too much water due to osmosis (Figure 25). The salts, proteins, and other solutes in their bodies attract water. Many freshwater organisms have waterproof coverings over at least parts of their bodies to limit water uptake. They do not drink water but consume it along with food. Producing large volumes of dilute urine can remove excess water. Species that live in bays and **estuaries** where rivers meet sea water may have to adjust to different levels of salinity.




https://en.wikipedia.org/wiki/Osmoregulation#/media/File:Bachforelle_osmoregulatoin_bw_en2.png

Figure 25. Salt and water regulation by freshwater fish.

As described in Chapters 3 and 6, water temperature varies much less than air temperature. Organisms in an aquatic environment are usually about the same temperature as the surrounding water. Fish and invertebrates in Polar Regions use molecules dissolved in their tissues as a form of antifreeze (Figure 26).



https://en.wikipedia.org/wiki/Notothenioidei#/media/File:Icefishuk.jpg

Figure 26. Several species of icefish evolved a natural antifreeze. The lack of blood cells is partially responsible for their transparency.

Aquatic mammals and birds must produce enough heat to balance the heat that is constantly being lost to the water, which is usually colder—sometimes much colder—than their body temperature. Fat is a good insulator. Some mammals have specialized fur that traps air close to

the body and keeps out water (Figure 27). Marine mammals with the longest evolutionary histories of life in the sea are hairless to reduce drag. They stay warm with fat alone. Birds that spend time in cold water have feathers for insulation, in addition to fat. Both fur and feathers require grooming with special oil glands to keep them water-resistant.

http://commons.wikimedia.org/wiki/
File:Mother_sea_otter_with_rare_twin_baby_pups_(9137192475).jpg

Figure 27. Sea otter mother and pups (*Enhydra lutris*). The mother puffs air into the pups' fur to help them float and stay warm.

The high density of water supports bodies better than air. Sea water is even denser than fresh water. Animals like the giant squid can be extremely active without a skeleton due to the support of sea water. Tiny organisms can float and reduce the energy needed to swim. Larger organisms may have special structures that allow them to float (Figure 28). Kelp is a type of seaweed that grows several meters from the sea floor to the light without investing in rigid tissue. Their air pockets keep their leaf-like fronds near the surface.

https://en.wikipedia.org/wiki/Fucus_vesiculosus#/media/File:Fucus_vesiculosus_closeup.jpg

Figure 28. Bladder wrack seaweed (*Fucus vesiculosus*) with gas-filled chambers.

Many species of boney fish have swim bladders that adjust their buoyancy by transferring gasses between their blood and swim bladder (Figure 29). When they have the same density as sea water (neutral buoyancy), they do not need to use energy to keep from sinking or floating.

Sharks and their relatives use an oily liver and the angle of their tail to help them keep their position in the water.

https://simple.wikipedia.org/wiki/Yellowfin_tuna#/media/File:Yellowfin_tuna_nurp.jpg

Figure 29. The yellow fin tuna (*Thunnus albacares)* is a fast-swimming fish with a swim bladder that allows it to adjust its buoyancy.

Water's density creates increasing pressure at greater depths. The pressure on an object at sea level is one atmosphere. As discussed in Chapter 6, this pressure is from the column of air above that object. Water is much denser than air, so 10 m of water creates as much pressure as that entire column of air. Every 10 m below the surface, the pressure increases by another atmosphere. The average depth of the ocean is about 4000 m and the deepest point is 10,000 m. If the base of Mount Everest were there, the entire mountain would still be under 2000 m of water. (Explore the effect of increasing depth on pressure with **Do Try this at Home: Water Pressure.)** As long as the pressure inside something equals the pressure outside, this is not a problem. You could drop an open can to the bottom of the ocean and it would not be crushed, but if you dropped a sealed one, it would be crushed as soon as the pressure difference between the outside and the inside of the can was greater than the can could support.

**Do Try this at Home: Water Pressure**

Take a large plastic container such as a gallon milk jug and punch two holes in it, one near the top and one near the bottom. Try to make these holes the same size. Have someone help you fill the jug in a sink or bathtub while you plug the holes (or fill the container first, then punch the holes).

Note how far the streams of water go. This is a result of the pressure of the column of water above the hole. Which one goes farthest away from the jug?

Deep-diving marine mammals have evolved mechanisms that allow their lungs to compress. They can still “hold their breath” because they have molecules called myoglobin that store oxygen in muscles. With their lungs collapsed, their bodies are denser and they can sink passively instead of swimming. To learn about the challenges that pressure creates for human divers, see **Make the Medical Connection: Decompression Sickness**.

**Make the Medical Connection: Decompression Sickness**

Scuba divers must understand the effects of water pressure. Have you ever shaken a sealed plastic bottle with carbonated liquid inside? When you look at the liquid inside the bottle, you do not see any bubbles, but when you start to unscrew the cap, many bubbles form. The bubbles are carbon dioxide. When the pressure inside the bottle was high, the carbon dioxide gas stayed dissolved in the liquid. When you released the pressure, the $CO_2$ came out of the liquid. If you release a tiny bit of the pressure at a time, you can avoid a big mess.

Most of the air around us (about 80%) is nitrogen. Divers breathe compressed air and are under pressure from the water above them. When a diver goes underwater, the pressure starts to force nitrogen gas into the blood and tissues. If the diver surfaces slowly, nitrogen slowly leaves the blood at the lungs.

If the diver surfaces too quickly, the nitrogen forms bubbles, creating a painful and potentially deadly condition called “the bends” or decompression sickness. Symptoms may show up immediately or hours later. The condition is treated by placing the diver in a chamber where the pressure can be raised, then slowly lowered to allow the nitrogen to leave safely.

The density of water also creates more drag for organisms that try to move quickly. **Hydrodynamic** bodies reduce drag and allow animals to reduce the cost of swimming. The cost of drag increases with speed. To reduce drag, fast fish move very little of their bodies. For example, tuna (Figure 29) use only their tails to reach high speeds. They keep their bodies rigid. Their fins might remind you of the wings of jet fighters because their shape reduces drag at high speeds. The fat that aquatic animals use as insulation also gives them smooth hydrodynamic shapes and buoyancy. Aquatic animals can also use behaviors, such as keeping appendages close to their bodies, to reduce drag (Figure 30).

https://commons.wikimedia.org/wiki/File:Euprymna_scolopes_-_image.pbio.v12.i02.g001.png

Figure 30. The Hawaiian bobtail squid (*Euprymna scolopes*) keeps its tentacles and arms held tightly together as it swims to reduce drag.

Fish and many invertebrates use gills to create a large surface area for gas exchange (Figure 31). The density of water supports the delicate gill structure. In air, most types of gills collapse, greatly reducing their surface area. This is why a fish will suffocate on dry land, even though the oxygen content of air is much higher than that of water. Fast-swimming fish may hold their mouths open as they swim to force more water over their gills and collect more oxygen.

https://en.wikipedia.org/wiki/Wikipedia:Featured_picture_candidates/Nudibranch#/media/
File:Nembrotha_cristata_2.jpg

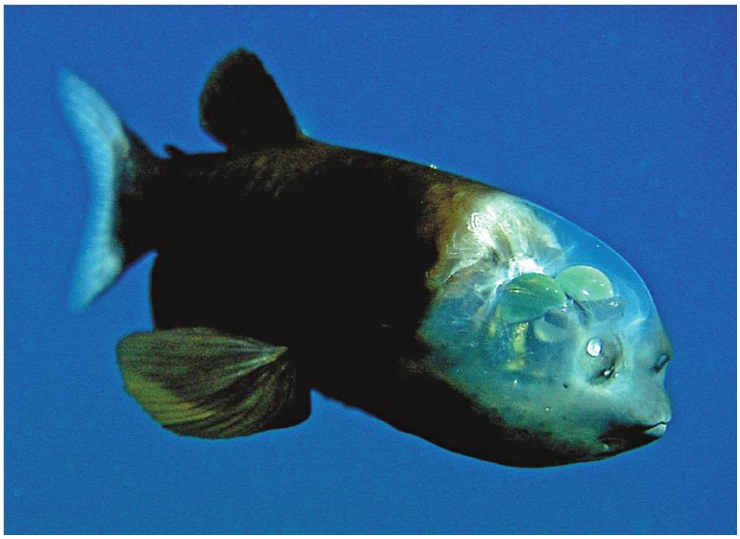
Figure 31. Sea slug or nudibranch (*Nembrotha cristata*) from Indonesia. The feathery green structures are a special type of gill. The name nudibranch means “naked gill” and refers to the lack of covering on the gills.

The aquatic environment also produces opportunities that are not available on land. Water is a good conductor of electricity. Some aquatic organisms in dark or murky environments may sense their environment by detecting bioelectricity. Others may produce electric currents of their own for navigating of for stunning prey (Figure 32).

https://en.wikipedia.org/wiki/Electric_eel#/media/File:Electric-eel.jpg

Figure 32 The electric eel (*Electrophorus electricus*) is not really an eel, but it can sense and produce electric current. It lives in silty water, so its eyes are not very useful. It can detect prey by sensing the electric current produced by the bodies of its prey. It can also stun them with electric current.

Species in many habitats have evolved bioluminescence—the ability of organisms to transform chemical energy into light energy. Bioluminescence can be used for signaling, attracting prey, confusing predators, or other purposes. The use of bioluminescence in the benthos is particularly effective because there are no other sources of light. Some species specialize on detecting bioluminescent prey (Figure 33)



https://en.wikipedia.org/wiki/Macropinna#/media/File:Macropinna_Microstoma.png

Figure 33. The barreleye (*Macropinna microstoma*) has a transparent head that allows it to detect light at very low levels. It can detect bioluminescent prey. The two greenish objects on the top of the head are its eyes. The darker features above the mouth are nostrils.

**Check Your Understanding**

- How do the physical properties of water influence the adaptations of aquatic species?
- How might the adaptation of saltwater species be different from those of freshwater species?

# Key Concepts

- Most water on Earth is salt water. Most freshwater is frozen or underground.
- Climate influences aquatic temperature, oxygen levels, and flow.
- Productivity in aquatic zones depends mostly on the availability of light and nutrients.
- High productivity often leads to low oxygen in aquatic systems.
- Rivers currents influence their nutrients, oxygen input, and species.
- Wetlands are important as habitat and buffers.
- Water in underground aquifers is vulnerable to overuse and contamination.
- Aquatic organisms have various adaptations to conditions such as salinity, temperature, water density, oxygen availability, and pressure.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately describe the conditions in different marine and freshwater life zones*
2. *Make and defend valid predictions about aquatic systems based on climate information*
3. *Make and defend valid predictions about productivity based on light and nutrients*
4. *Correctly explain how flow, temperature, salinity, and other factors influence adaptations of species*

1. Compare lakes and oceans regarding key factors (*Learning Outcome 1*):
   A. Which have a greater proportion of surface area to volume?
   B. Which have a larger aphotic zone?
   C. Which have greater pressure in the benthic zone?

2. Refer to Figure 34.

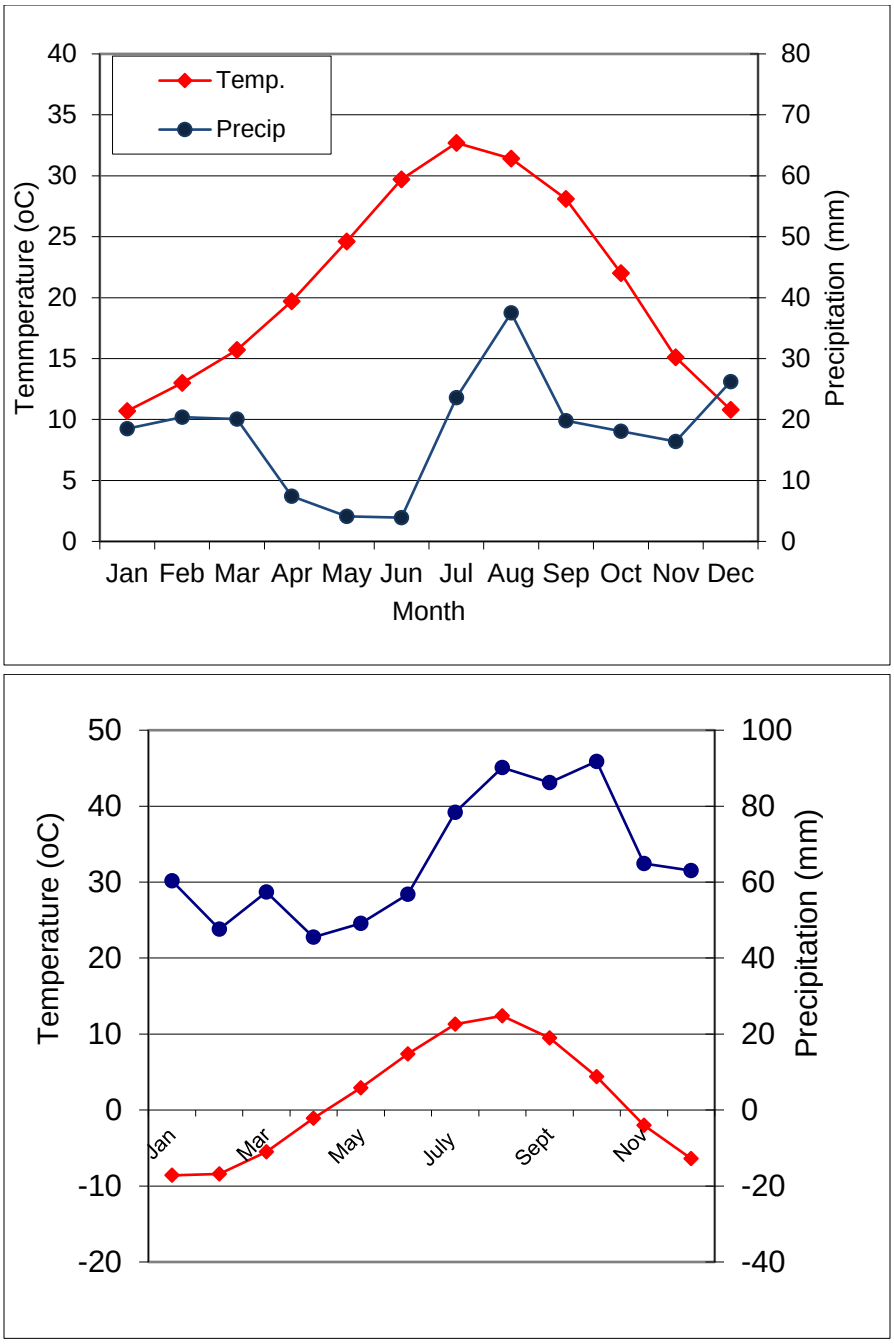



Figure 34. Climate graphs from Tucson, AZ, USA (top) and Petropavlovsk, Kamchatka, Russia (bottom).

A. Which locations will have a greater volume or water in rivers? Explain your answer.
B. Which location will have more *consistent* river flows?
C. Which location will have lakes that will be covered with ice for part of the year?
D. Which location will probably have more nutrients in the water? Explain your answer. (*Learning Outcome 2*)

3. Some fish, such as salmon, hatch in freshwater pools, then live for years in the ocean before swimming up rivers and returning to freshwater pools to reproduce.
    A. What sorts of different conditions would they encounter?
    B. Why is this pattern rather rare? (*Learning Outcomes 1 & 4*)

4. Why are plants common on the edge of lakes while phytoplankton are common in the open ocean and the open lake zones? (*Learning Outcome 3 & 4*)

5. Antarctica experiences extremely long days during the summer. Ocean currents carry nutrients toward the Antarctic continent, then up the continental shelf into shallow waters. How would this influence productivity? (*Learning Outcomes 2& 3*)

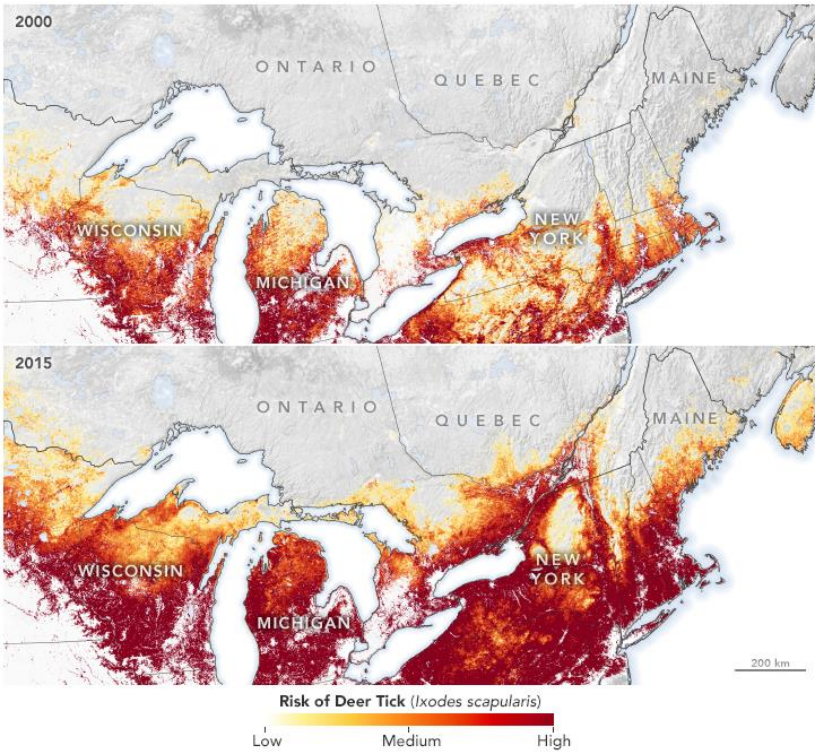
6. The Mississippi River carries millions of tons of nutrients into the Gulf of Mexico. This has resulted in a huge “dead zone” with no oxygen. Explain how the nutrients cause the anoxic conditions. (*Learning Outcome 3*)

**Unit III: The Living World: Limits of Life**

# Chapter 10: Where Species Live: Range and Distribution

### Case Study Part 1: Diseases Invade the North

Regions with cold, dry air may make it difficult for disease organisms to live outside of the bodies of the species they infect. Individuals may also be spread out, especially during seasons when food is scarce. Lyme disease is one example of a **pathogen** (disease-causing organism or virus) that is expanding its range farther north as temperatures increase (Figure 1).




https://www.naturalhazards.nasa.gov/images/148482/mapping-the-spread-of-lyme-disease

Figure 1. Expansion of Lyme disease northwards between 2000 and 2015.

Lyme disease is caused by a bacterium that infects deer and blacklegged ticks. The tick parasitizes many animals, including humans, deer, and deer mice. When an infected tick bites a human, the bacterium enters the host's bloodstream. Early symptoms (headaches, body pain, chills, fever, and fatigue) may be mistaken for the flu. Antibiotics usually cure the disease. If the disease is not treated, it can cause heart and joint problems and spread to the nervous system.

Other human and wildlife pathogens are moving further north. These include *Giardia* (a microbe that causes intestinal disease), *Trichinella* (a parasitic worm that humans can get from eating undercooked meat), and *Toxoplasma* (which is very dangerous for developing fetuses).

**Learning from the Case Study**

- Why might a changing climate change where species can live?
- How might increasing wildlife diseases affect humans?
- Could changes in where parasites are found change where wildlife are found?

# Learning Outcomes

1. *Apply concepts of habitat, range, distribution, and habitat selection to describe where species are found*
2. *Draw reasonable conclusions about how biotic and abiotic factors influence range*
3. *Explain why the size of a species' range may shrink or grow*

**Vocabulary Toolkit**

**Opposites**

Native species and non-native species

**Word Watch List**

**Pathogen**: A virus or organism that can cause disease
**Habitat**: Area where species can live, contains necessary conditions and resources
**Optimal habitat**: Highest quality habitat for a species
**Marginal habitat**: Habitat that barely meets survival requirements for a species
**Habitat sink**: A habitat where loss of individuals exceeds production of individuals
**Geographic Range**: Region that contains suitable habitat for a species
**Distribution**: Pattern in space, either geographic range of a species or the local pattern of individuals in a population
**Native species**: Species that have evolved in the region of interest
**Non-Native species**: Species that have evolved in a different region and spread to the region of interest
**Invasive species**: Non-native species that are rapidly expanding their range, usually at some environmental cost
**Home range**: Area in which an individual is usually found
**Sessile**: Describes organisms that cannot move around on their own after their juvenile phase
**Habitat selection**: Behavior that causes animals to use particular types of places
**T-test**: Statistical test that compares sample means from two populations, used to determine whether the population means are likely to be different. Results are influenced by sample size, variation, and difference between sample means
**Significant difference**: Finding that it is unlikely that a variable has the same value in different populations, based on the samples and a statistical test

## Species Exist in Specific Habitats

As discussed in earlier chapters, climate creates life zones. Organisms adapt to these zones in the short-term using physiological adjustments. Species may also change in the long term due to evolution by natural selection. Organisms may be able to move between environments. The environment of an individual also includes other organisms. This chapter will explore how the living and non-living environment influence where species live, including how the behavior of individuals leads to larger patterns. Later chapters will explore further how individuals interact with other members of their own species and members of other species.

A **habitat** is a place where an individual lives. Habitats provide resources and are within a life zone that the individual can tolerate. The habitat for a species of mushroom might be a moist temperate deciduous forest. The habitat for a pneumonia bacterium might be your lungs. The habitat of the Channel-billed toucan is the tropical rainforest (Figure 2). Only some regions within that tropical rainforest will allow the survival of these toucans. The climate must be suitable. Food sources, tree cavities for nesting, and other resources must be there.

http://commons.wikimedia.org/wiki/File:Channel-billed_Toucan_(Ramphastos_vitellinus)_(4089510455).jpg

Figure 2. Channel-billed toucan (*Ramphastos vitellinus*) in its habitat, the tropical rainforest of South America.

Other species can be critical in making a habitat suitable. In the case of the toucan, some species will be helpful—providing food, shade, or nesting sites. Some species will compete for the same resources, be a predation threat, or cause disease. The toucan will provide vital services to other species, such as seed dispersal. These topics will be discussed more in Chapters 14 and 15.

Species can tolerate certain ranges of variables in their habitats. For example, a marine species may be able to tolerate only certain ranges of temperature, salinity, depth, or pH. A plant may only be able to tolerate certain climates, soil chemistry, or light conditions. Some habitats are **optimal**, meaning that they are the best possible for a particular species. Others are **marginal**, meaning that they are just barely adequate for survival. Individuals in marginal habitats might be

unhealthy or unable to reproduce. Slight changes might make marginal habitats uninhabitable by the species.

Optimal habitats can act as a source of individuals for marginal habitat. When agencies protect areas to preserve species, they try to include optimal habitat. For example, a marine reserve where harvesting is not allowed will include habitat that is as close to optimal as possible. The idea is that more fish (or other organisms) will be produced in the protected area than can survive there (Figure 3). The "extra" individual will disperse to other areas where they can be harvested while the fish that are doing most of the reproducing are protected. Areas with marginal habitat, or where harvest is allowed are often called **sinks** because they drain individuals from the source area. Quality of a habitat depends on the species, so when agencies are deciding which areas to protect, they may have to balance the needs of different species.

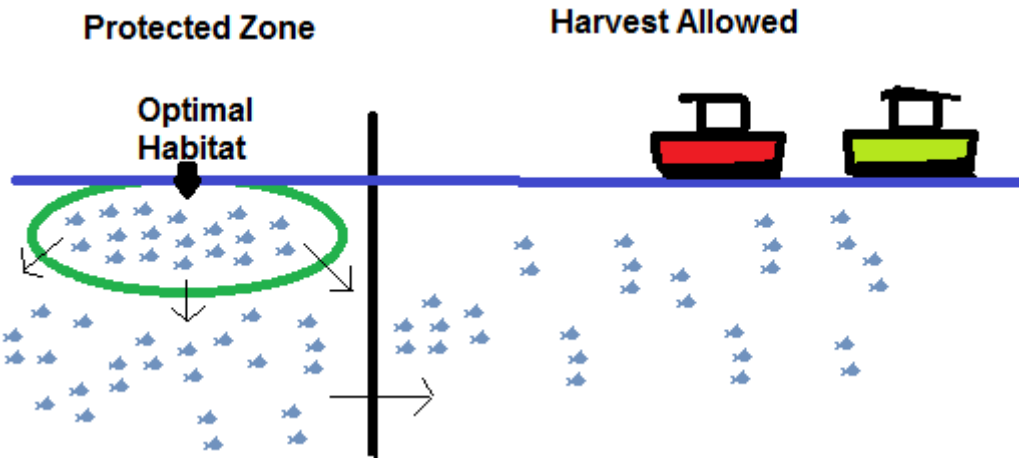



Figure 3. Protected zones with optimal habitat can be a source for species that are harvested in other areas. Excess individuals from optimal habitat can be harvested in sink areas without while protected individuals continue to breed.

### Check Your Understanding

- What is a habitat?
- What factors may be important in determining the habitat of a soil microbe or a marine algae?
- How might you measure the difference between optimal and marginal habitat?

### Geographic Ranges Include Habitat Suitable for a Species

If you were to look at a map and identify where you might find a species, you would be defining its **geographic range** or **distribution**. When a map shows that the range of a particular species includes all of your state, this does not mean that your entire state is suitable habitat for that species, only that your state contains suitable habitat for that species scattered throughout your state. For example, a certain fish species may be very common in lakes in your state. A range map may show the entire state, including the land. Because ranges are at a larger scale, detail is lost. The Channel-billed toucan's range includes part of northern South America (Figure 4). This does not mean that the entire area is suitable habitat for this toucan, only that those

regions contain suitable habitat somewhere. Often range maps will show different patterns for the same species, depending on the criteria used to draw them.

https://en.m.wikipedia.org/wiki/File:Ramphastos_vitellinus_range.png

Figure 4. Range of the Channel-billed toucan shown in blue.

There are about 40 species of toucans and their close relatives. Each has its own specializations for different habitats and resources. The mountainous terrain around their range could have led to macroevolution because the different climate zones at different altitudes could have led to selection for different traits. The mountains could also have separated populations so that they couldn't interbreed. For more information on why there are so many species, see **Evolutionary Perspective: Geographic Isolation and New Species**. For a discussion of why some species might be more widely distributed than others, see **Hypothesis Testing: Does Genetic Variation Drive Geographic Range?**

**Evolutionary Perspective: Geographic Isolation and New Species**

Recall from Chapter 4 that when populations of the same species can interbreed, the populations usually have similar gene frequencies, but isolated population may change due to random events or local adaptations until the original species becomes two or more species. Ranges can be divided by many processes, including climate or geological changes. The macroevolution that results is called allopatric speciation (allo = different, patria = country).

The habitat of spotted owls is mature conifer or mixed conifer and deciduous forests. Spotted owls (Figure 5) were apparently separated over 100,000 years ago as the southwestern United States became hotter and drier and became desert and grassland. The northern, California, and Mexican spotted owls are now separate subspecies. In time, they may become separate species.

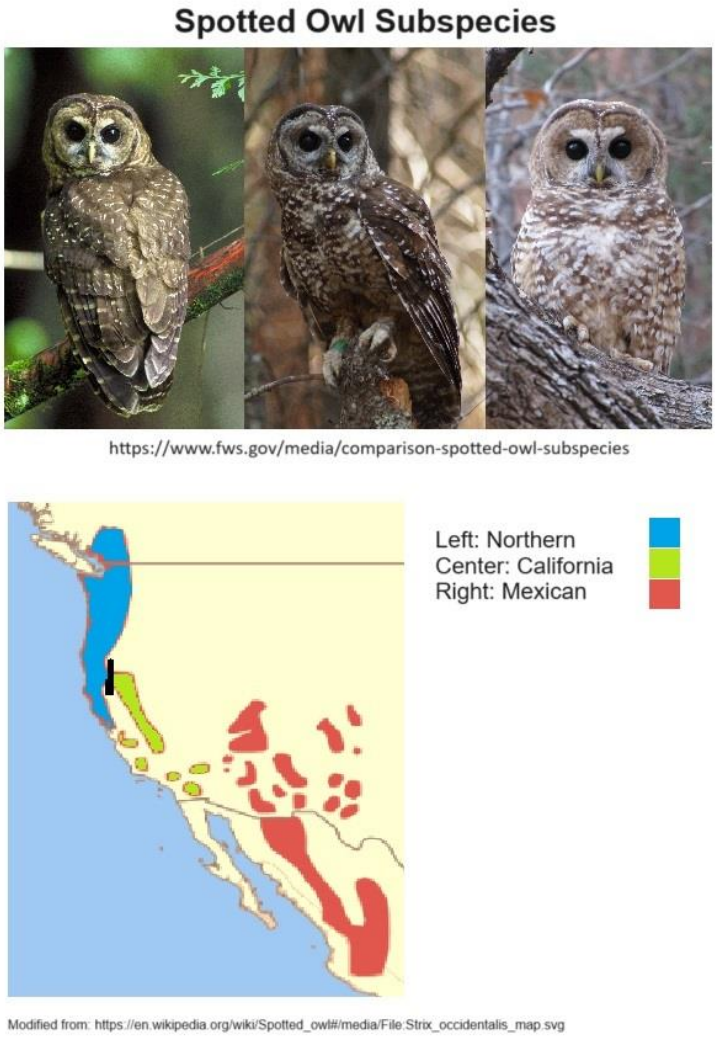



Figure 5. Subspecies distribution in spotted owls (*Strix occidentalis*).

**Hypothesis Testing: Does Genetic Variation Drive Geographic Range?**

What determines whether a species has a narrow or a wide distribution? Is it a matter of chance, with certain species just arriving first at many sites? Are some species more physiologically flexible and able to adjust to varied conditions? Do some have genes that allow them to live in a wider range of climates?

Recall that mutations do not happen because they are needed; they are the result of random mutation. If the allele doesn't exist in a population, there can be no microevolution to make it more common. For example, fruit flies (*Drosophila*) can be vulnerable to cold and dry conditions. Certain loci control traits related to cold and desiccation (drying) resistance. If a species has a lot of variation at these loci, then there's a chance that one or more of the alleles will be useful and become more common. *Drosophila* species that are more resistant to cold or desiccation can successfully live in a wider variety of climates. Could this lead to a wider distribution for species with more variation in alleles for resistance to cold and desiccation?

Hypothesis: Lack of genetic variation limits distribution of fruit fly species. Widespread species have genetic variation at loci related to resistance to cold and drying.

Kellerman et al. (2009) categorized many species in the fruit fly genus *Drosophila* as either widespread or restricted to the tropics. They then measured how resistant the flies were to desiccation and cold (Figure 6).

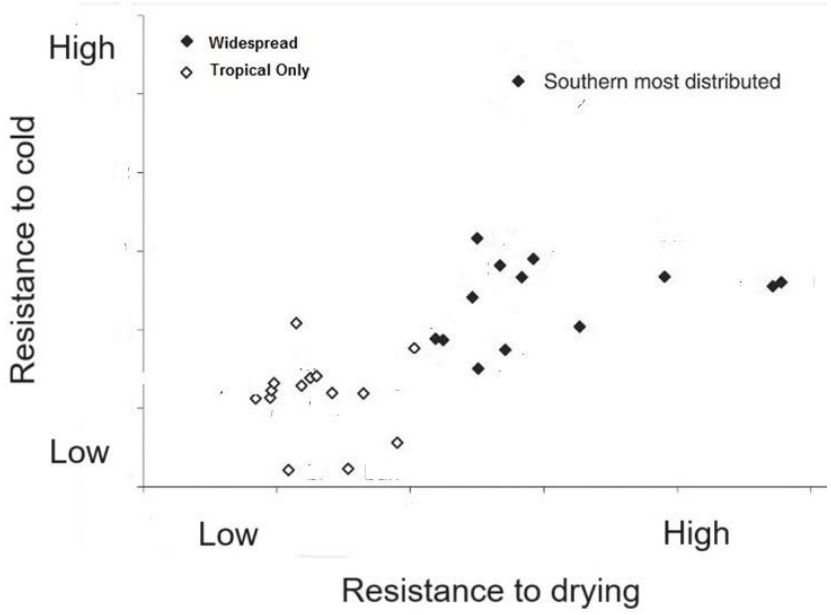



Figure 6. Correlation between resistance to drying (dessication) and cold resistance. Letters refer to *Drosophila* species. The species *Drosophila funebris* (fun) is an outlier. Modified from: Kellermann, V., van Heerwaarden, B., Sgrò, C. M., & Hoffmann, A. A. (2009). Fundamental evolutionary limits in ecological traits drive Drosophila species distributions. *Science*, *325*(5945), 1244-1246.

**Analyze the Figure**

- Which category of *Drosophila* (widespread or restricted to tropics) had higher resistance to cold and drying?
- Were resistance to drying and resistance to cold correlated with each other?

Previous studies had tried artificially selecting some desiccation-sensitive Drosophila for resistance to desiccation but failed. This would support the hypothesis that those species lacked alleles that would increase their resistance to desiccation.

In separate analyses, researchers found that widespread species had significantly more variation at desiccation-resistance and cold-resistance loci than tropical species had. One could explain low genetic variation as a result small populations in the past of the species (see Chapter 3). If small populations were the cause of the low genetic variability in the cold resistance and desiccation resistance loci, we would expect low variability at all loci in the tropical *Drosophila* species. Researchers found no difference between tropical and widespread species in the level variation at loci for wing length.

**Evaluate the Hypotheses**

- Is the hypothesis supported or refuted by the data? Provide evidence to support your conclusion.
- If the geographical range of some species is limited by genetic variation in traits related to heat resistance, how might global climate change influence the number of species in warm climates?
- What experiment would you do next?

**Misconception Alert: If one area is destroyed, species can go somewhere else.**

**FALSE.** An area must meet all the needs of a species to be suitable habitat. For example, if warming temperatures make southern areas of a North American plant's range too hot and dry, it may seem like the plant would just grow farther north. But soil conditions, pollinators, or seed dispersers may not be present farther north. Any species moving into a new area will also probably face competition from established species. Animals may have instinctive behaviors that prevent them from identifying or using new areas.

**Check Your Understanding**

- What is the difference between a habitat and a geographical range?
- What influences the geographical range of a species?
- Will a range be larger or smaller than a patch of suitable habitat?

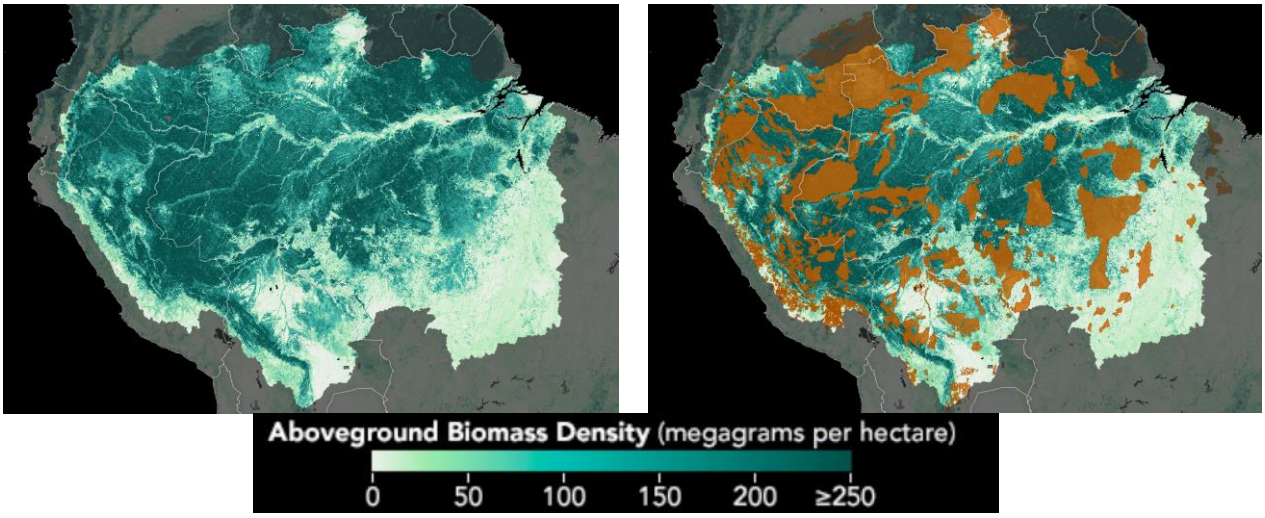
**Species Ranges Can Shrink or Grow**

Disappearing habitat threatens many species. The Painted bunting (Figure 7, *Passerina ciris*) requires large areas of coastal shrub and grassland for successful reproduction. This coastal land is valuable for beachside development. Numbers of these birds have been declining approximately 4.6% a year since 1966. Habitat loss is probably the most important cause, but they are also illegally trapped and sold as pets. As habitat of a species is destroyed, ranges usually shrink, but the range could still have the same outline and just include fewer or smaller suitable habitat patches. For more on human activity and habitat loss, see **Why It Matters: Habitat Loss**.

http://commons.wikimedia.org/wiki/File:Passerina_ciris-20090208.jpg

Figure 7. Male Painted bunting (*Passerina ciris*). Habitat loss may be an important factor in their decline.

**Why It Matters: Habitat Loss and Social Justice**




https://earthobservatory.nasa.gov/images/151921/indigenous-communities-protect-the-amazon

Figure 8. Deforestation in the Amazon Basin indicated by lighter colors. The map on the right superimposes land managed by indigenous communities (brown).

Habitat destruction is the major cause of species extinction. The rainforests of the Amazon Basin have been damaged by logging, development, and agriculture. Habitat can be completely lost, or fragmented into areas that are too small to support a population.

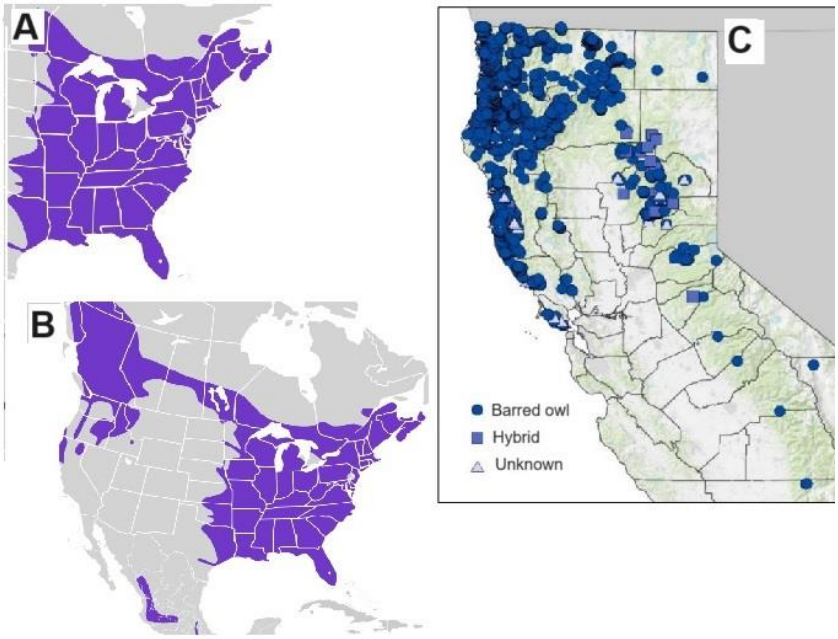
Deforestation is driven by global economic forces, such as the international market for beef and soybeans. It tends to spread from rivers and roads. The rate of deforestation in the Amazon has decreased in recent years due to government action and consumer pressure. Indigenous communities have also actively protected natural resources.

- Families may feed themselves by farming in the rainforest. Is it fair for local governments to stop them or punish them?
- Should the United States regulate beef and soybean imports to encourage sustainable practices by large agribusinesses and small ranchers and farmers?
- Should the international community have any say in how the countries of the Amazon Basin manage their own resources?

Ranges can expand because of increases in suitable habitat. As one species expands, it may take over habitat of another species. For example, barred owls (Figure 9) have expanded their range in North America (Figure 10). This may be because trees are now much more common across the former prairies. Native Americans used fire to maintain grass for the use of bison and horses. European settlers suppressed fires and planted trees, which provided nest sites, protection, and habitat for the prey of the owls. The barred owl range expanded into the range of spotted owls, resulting in competition and hybridization. Loss of habitat to logging and development probably also contributes to the decrease in spotted owl populations.

http://commons.wikimedia.org/wiki/File:Barred-owl-chick-58.jpg

Figure 9. Barred owl (*Strix varia*) adult and chick.




Adapted from: https://en.wikipedia.org/wiki/Barred_owl#/media/File:Strix_varia_map.svg and https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=166159&inline

Figure 10. A. Range of the barred owl (*Strix varia*) in the United States and Canada in 1910 and B present day. C. Area where barred owls and northern spotted owls (*Strix occidentalis caurina*) overlap and hybrids are found.

Changes in climate can also expand or decrease the range of a species. For example, as ice ages come and go, species move farther south and north. As entire continents have moved, habitats changed drastically, so we find fossils of ferns in Antarctica. Currently, migratory birds are wintering farther south.

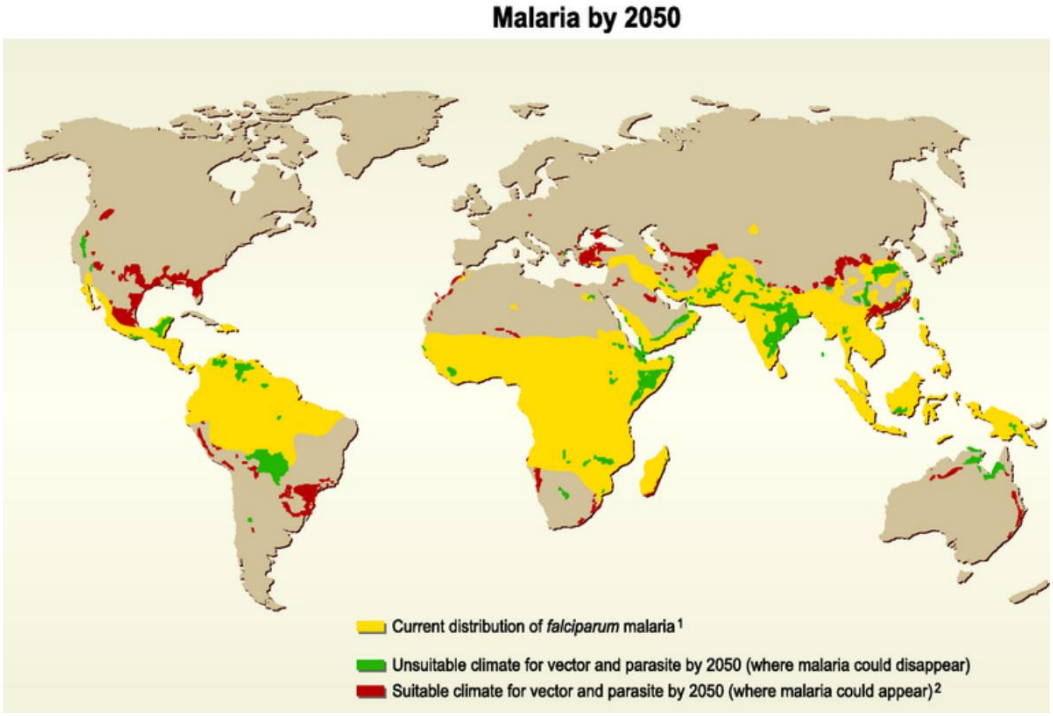
**Case Study Part 2: What Happens as Pathogens Spread North?**

Warming temperatures cause earlier snow melt and a longer growing season for plants in the northern part of the northern hemisphere. Populations might be larger because there is more food. Increasing host densities can lead to more disease transmission. When ranges expand and movement patterns change, species that were separated can start to interact. One potential interaction is sharing of diseases. The spread can be direct, such as an individual eating a dead, diseased animal. It can be indirect, such as when an insect or tick feeds on the blood of a diseased animal, then feeds on the blood of another animal. For more on how human diseases might be influenced by warming and range shifts, see **Make the Medical Connection: Malaria Spreads North**.

**Learning from the Case Study**

- Could diseases limit the range of their hosts?
- Could changes in migration influence disease transmission?

**Make the Medical Connection: Malaria Expands its Range**




https://www.eea.europa.eu/data-and-maps/figures/malaria-in-2050

Figure 11. Potential expansion of the range of malaria by 2050. Current range of malaria is shown in yellow. Potential new areas are red. Areas in dark grey indicate regions that would no longer be suitable for malaria. These predictions are based on models of climate change.

Malaria is an international killer. The parasite that causes malaria is spread by certain species of mosquito. These mosquitoes then transmit parasites to humans. Deforestation in places like the Amazon basin has greatly increased the number of people infected with malaria as more habitat for the mosquitoes is created.

If global temperatures increase only 2-3 $^{o}$C, several hundred million people would be at risk for malaria. For other people, the risk of malaria would decrease as habitats became less suitable for the species that spread malaria. Several other diseases could potentially be influenced by changing habitats.

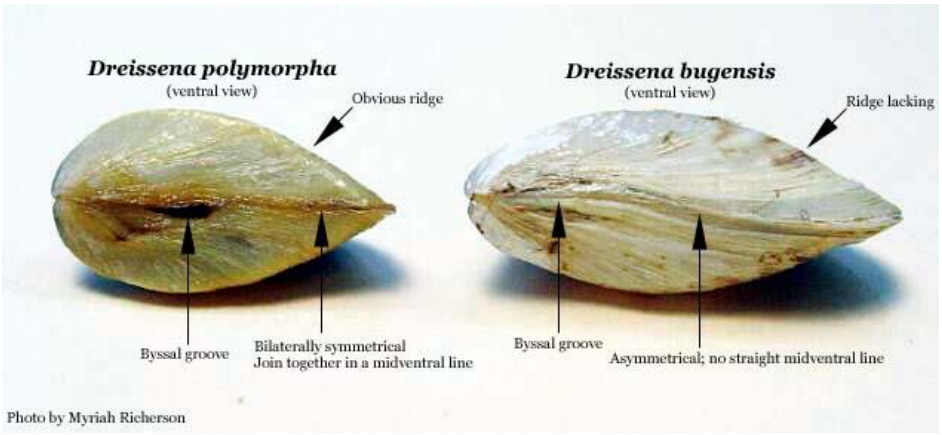
Sometimes ranges expand because species travel or are transported to a new area that is suitable for them. Humans have expanded the range of many species, sometimes on purpose, sometimes by accident. Even before recorded history, explorers took domesticated plants and animals with them as they settled new areas. Pathogens and pests often travelled with them also. The species that evolved in a particular place are called **native species**. They can be threatened by **non-native** species. The new area probably does not have predators, prey, or

pathogens that evolved with the non-native species. So if the habitat does meet their needs, the non-native species may expand quickly, and crowd out native species. We call these **invasive species**.

Ocean-going ships carry marine organisms from one place to another. They may be attached to the ships, or travel in ballast water that ships carry to add weight to a ship to keep it stable when its cargo is light. This water may be transported to the other side of the globe, then dumped when the ship loads a heavier cargo. Many marine organisms have tiny larval forms that survive the journey.

An example of an invasive species is the zebra mussel (Figure 12). It travelled from Europe to the Great Lakes of the United States in ships that travelled up canals from the Atlantic. It was first found in the late 1980's. The habitat of the Great Lakes turned out to be excellent for the zebra mussel and it quickly invaded, covering the bottom of lakes and many human-made structures. Zebra mussels threatened many native mussels and clams with extinction. The mussels travelled in and on recreation boats that were transported to smaller lakes, spreading as far as California. The cost of direct damage and of changes to lakes is in the billions of dollars. The good news is that zebra mussel numbers have decreased in some places. The bad news is that they were replaced by an even more successful invasive species, the quagga mussel.

**A**




http://nas.er.usgs.gov/queries/factsheet.aspx?speciesid=95

**B**

http://en.wikipedia.org/wiki/Bivalvia#/media/File:Zebra_mussel_GLERL_4.jpg

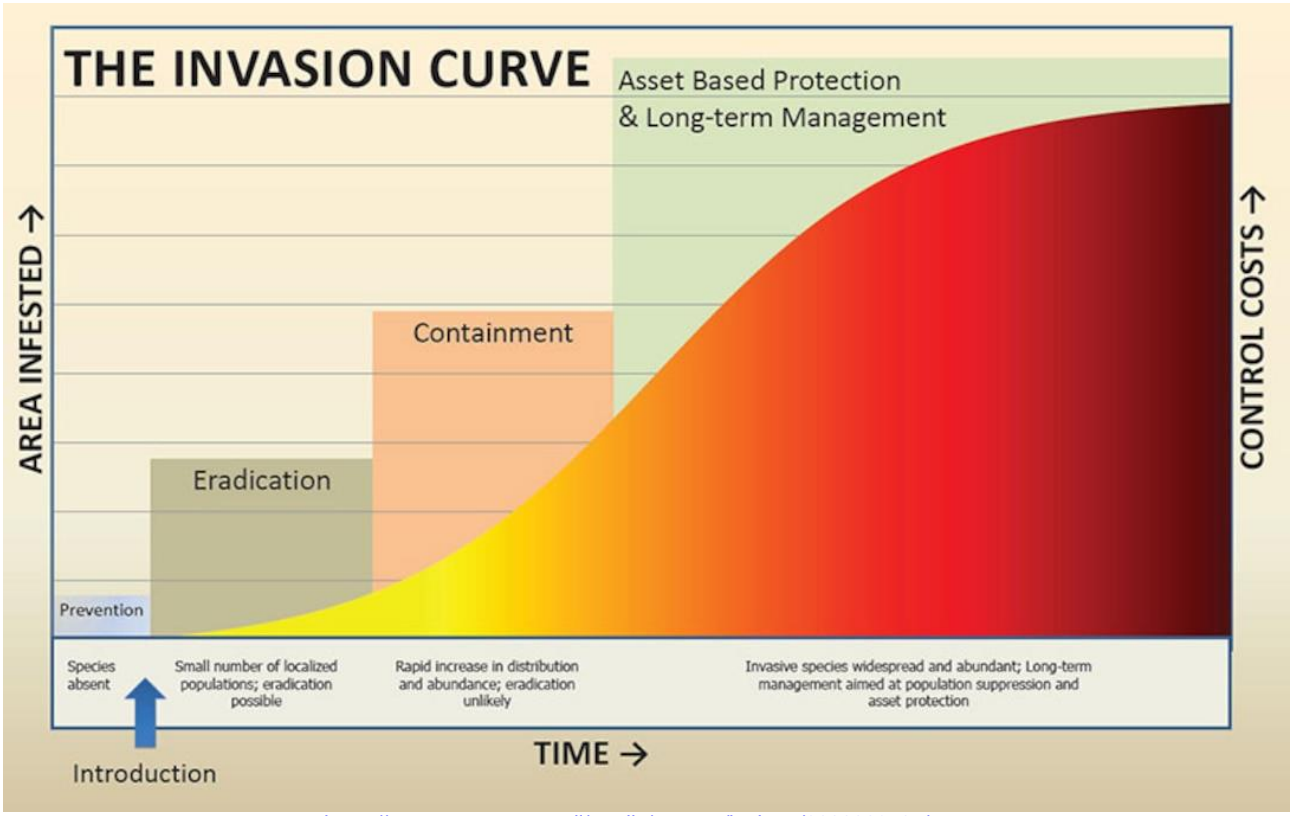
Figure 12. **A**. Zebra (*Dreissena polymorpha*) and quagga mussels (*Dreissena bugensis*. **B**. Zebra mussels have completely covered the bottom part of the scientific instrument in Lake Michigan.

Sometimes species adapt to using urban habitats. For example, red foxes have adapted to living in cities (Figure 13). They probably invaded British cities in the 1930's and have spread to many European urban areas. They eat garbage and small urban-dwelling animals, such as pigeons and mice. Their only predators in the city are large dogs. Their range also expanded when Europeans imported red foxes to Australia in the early 1800s.

https://upload.wikimedia.org/wikipedia/commons/1/1c/Urban_fox_379.jpg

Figure 13. Red foxes (*Vulpes vulpes*) have adapted to urban areas.

As invasive species colonize a new area, it may take a while for them to be noticed. Even when authorities have detected them, it may take a while for anyone to act, allowing them to spread even further. Once invasive species become established, eradicating (eliminating) them is almost impossible (Figure 14).




https://www.usace.army.mil/Media/Images/igphoto/2000809105/

Figure 14. A model of how invasive species increase their range and how the cost of controlling them changes.

**Analyze the Figure**

- Does the cost of controlling invasive species increase linearly as the species expand their range, or do costs rise faster and faster?
- Why does “containment” replace “eradication” as a control measure?

**Check Your Understanding**

- What factors might cause the range of a species to shrink?
- What factors might cause the range of a species to expand?
- Why might a non-native species become an invasive species?
- How might invasive species influence the range of native species?

**Local Distribution Patterns Vary Between Species**

It is useful to understand the local distribution of individuals within a species. Sessile animals (such as barnacles) never move after settling as juveniles. The distribution of individuals in a non-sessile species is based on the **home ranges** of individuals. A home range is the area where the individual usually is. Think about your own movement patterns, you probably travel around in the same general area as you go to class, work, do chores, or have fun. If you take a trip to a distant place on vacation, that is not part of your home range. Your home range probably overlaps with the home ranges of many other people. Some animal species are nearly always solitary, while others are rarely alone. There is a much smaller area—such as your home—that you would defend from intruders. This is similar to an animal’s territory. This will be discussed in Chapter 11. (For a discussion of how mobile individuals are counted, see **Model Skill: Estimating Numbers with a Mark-Recapture Model**)**.** Plants, fungi, and other **sessile** species stay in one place once they start to grow, so their distribution is more fixed.

Some species determine the distribution of other species. Toucans eat whole fruits. When they defecate, they may “plant” the seeds of that fruit far from the parent tree. If there are several seeds in one deposit of waste, this may lead to a small clump of seedlings. If the toucan were to defecate as it flew through the forest, seeds might be distributed randomly, meaning that there might be no consistent minimum or maximum difference between individuals of the fruits it “plants” (Figure 15).

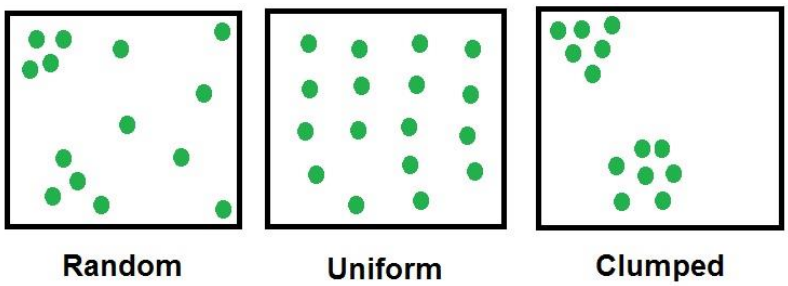
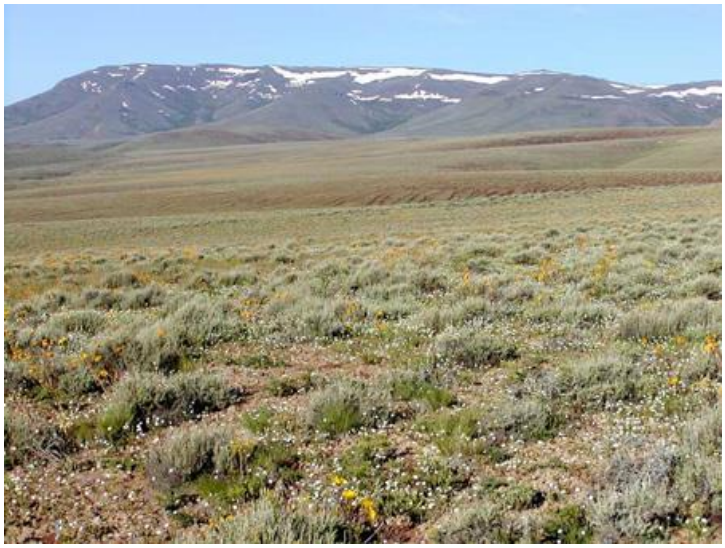



Figure 15. Patterns of local distribution. Each dot represents an individual. A sample random distribution is shown, but random distributions do not follow any pattern. An actual pattern may not fit neatly into any category.

If resources are scarce, one individual may take all the resources right around it, preventing other individuals from growing close to it. In sessile organisms, this will result in a uniform pattern because only seeds or spores that are a certain distance from other plants of the same species will survive (Figure 16). If a plant or other sessile individual gives off chemicals that harm other individuals of their species, this can also create a uniform pattern. In animals, territoriality leads to more uniform distributions because it limits how close individuals will be. Crops are intentionally planted in uniform distributions that will allow the most crowding possible while still allowing plants to get the resources they need.



http://www.fs.fed.us/database/feis/plants/shrub/artarb/all.html

Figure 16. Uniform distribution of sagebrush (gray-green shrubs, *Artemisia arbuscula*) in grassland/shrubland in Malheur County, OR. Water is usually limited, so plants are farther apart than a random or clumped distribution.

If a bird that disperses seeds tends to perch in the same place when it defecates, a clump of that species of plant may grow up there. A clumping pattern can also result when seeds or spores fall near a parent plant, when individuals grow better together—helping to shade each other or break into the soil, for example—or when resources are in discrete patches (Figure 17). Sessile organisms that reproduce asexually using special roots will grow in a clump because they are attached. Animals may have a clumped distribution when resources are patchy or when animals stay together for protection from predators or to find food. Sometimes a group of individuals are necessary for a task, such as hunting a larger animal.

https://en.wikipedia.org/wiki/Armillaria_tabescens#/media/File:Armillaria_tabescens.JPG

Figure 17. Clump of honey fungus (*Armillaria mellea*) in temperate deciduous forest in Great Britain. When resources are patchy, or seeds or spores tend to fall in the same place, distribution tends to be closer together than random distribution.

**Check Your Understanding**

- What factors might lead to a clumped distribution?
- Why might some species have a dispersed distribution?
- Why might a plant benefit if its seeds were spread far away from it?
- Which distribution is most likely to increase the spread of pathogens?

**Model Skill: Estimating Numbers with a Mark-Recapture Model**

Mobile animals can be difficult to count. Ecologists use a variety of methods, from spotting moose from airplanes, to collecting wolf feces, to counting nests. Another approach is to capture animals, mark them in some way, release them, then capture another sample from the same population. If both samples (results of the first and second capture attempts) are random, the proportion of all marked animals in the total population should be the same as the proportion of captured, marked animals to the total number of animals caught in the second sample (Figure 18). This allows us to solve for N, the total number.

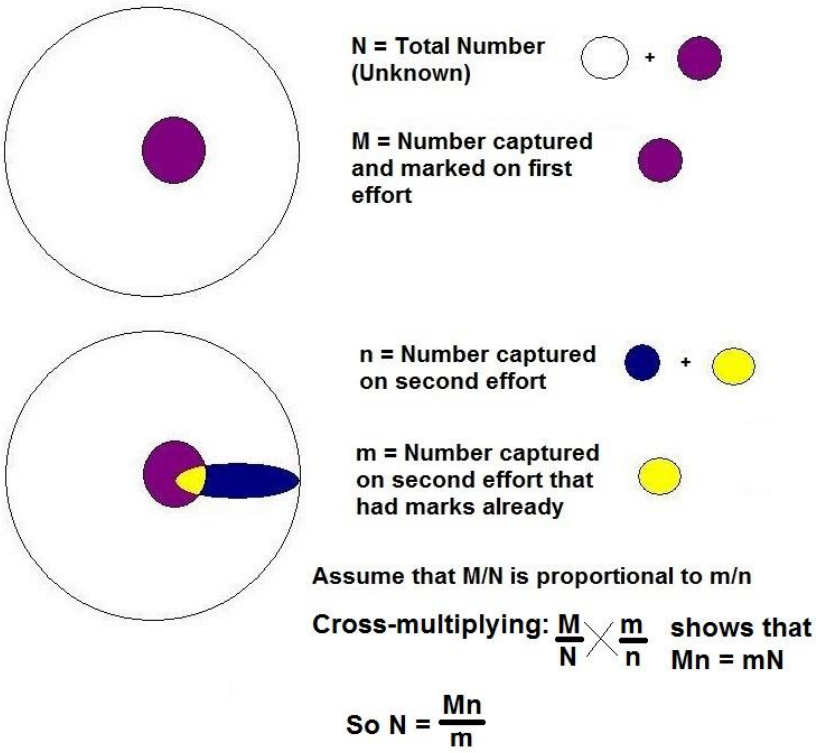



Figure 18. The Lincoln-Peterson model for estimating population size based on marking and recapturing animals.

This is the Lincoln-Peterson model. It has 4 main assumptions:

- All individuals in the population are equally likely to be caught, marked or not.
- No individuals are born or leave the area between the capture attempts
- Marked and unmarked individuals are equally likely to die or leave the area
- No marks are lost

These assumptions may not always be met, but the method can give reasonable estimates of population size. Some adjustments of the model improve its accuracy.

**Organisms May Select Their Habitats**

Animals and some single-celled organisms can move to more suitable habitats. Aquatic invertebrates might move into the upper levels of a lake at night to eat phytoplankton, then swim down into the aphotic zone during the day to avoid predators that hunt by sight. Marine iguanas may forage in the cold water, then sun themselves on dark rocks. Migratory birds might move long distances twice a year to take advantage of local food abundance and good weather for raising their young. Young of many species disperse from the place they were born or hatched to seek new habitats.

**Misconception Alert: Only Animals Select their Habitats**

**FALSE.** Many single-celled organisms move to environments that have more food or better abiotic conditions. Plants send more roots to areas with more needed resources. Some will turn to face the sun. The organism does not have to "know" why it is selecting the habitat.

Ecologists usually compare habitat use by an animal with the availability of the habitat. For example, if 70% of the edge of a pond is covered by aquatic plants, but juvenile fish stay in the area with plants 90% of the time, they are using the habitat at a greater rate than one would predict due to chance alone. The way an animal chooses a habitat is **habitat selection**. The animal does not have to be making any conscious decision. It may just respond due to reflexes. It might also have a complex response to cues that are both learned and instinctive.

It might seem like an individual would consistently choose optimal habitats, but that isn't always true. The individual might not find a good habitat because it doesn't know where to go. The area may already be full. The cues that trigger an animal to settle in an area may not be reliable. For example, some birds choose areas where leaves have already sprouted. Unfortunately, non-native trees have invaded their range. These trees sprout their leaves early but do not provide food for the birds. In the future there may be selection for more reliable cues of habitat quality, but only if random mutation creates genes that lead to the behavior.

Sessile organisms do not get to choose their habitat in the same way. Plants can select the habitat of their roots by growing them toward resources (such as water or nutrients) or away from danger (such as toxins). Fungal hyphae (which function almost like roots) can do the same thing. Seeds or spores may be carried by wind, water, or other species. The organisms cannot control this movement, so parents may have to produce many seeds or spores for some to reach suitable habitat.

**Model Skill: Statistical Testing**

Imagine that you wanted to find out whether the trees of a particular species were taller on the north side of a mountain than on the south side. If you measured every single tree, you would have your answer. You would have the average values for both populations and could just see if they were different. Researchers rarely have the ability to measure the entire populations, so they must rely on samples, which are a subset of the population. To be statistically valid, the samples must be drawn randomly, with every tree having an equal chance of being included in the sample. (Review Chapter 1 or Appendix B for a discussion of random samples.) It would be surprising if the average height of the trees in your sample were *exactly* the same on both sides of the mountain. But how different do the *samples* have to be before you would conclude that there was a difference in the *populations* of trees? Did you just happen to get a few tall trees on one side and a few short ones on the other side?

Scientists use statistical tests to answer questions like this. To compare the values for the tree height samples, one could use a **T-test**. This test helps to answer the question, "If two populations had the same mean for this variable, what is the probability that any random samples I drew would be at least this different?" The test compares how different the sample means are and how much variation there is in each of the samples. For example, if all the trees on a given side were pretty much the same size, it would be unlikely that you would just happen to get enough unusual trees to throw off your sample. On the other hand, if trees varied a lot in height on that same side, it would be comparatively easy to get several trees that were exceptionally tall (or short) due to chance. The test also takes into account the size of your sample. It is much more likely to get two very tall trees by chance than to get 20 very tall trees by chance.

Imagine that the mean for trees on the north slope were 10.5 m, while those on the south slope were 9.75 m. The samples could have a lot of variation within them (Figure 19 A) or very little (Figure 19 B). The sample with little variation might have a significant difference between the samples, while the one with more variation might not.

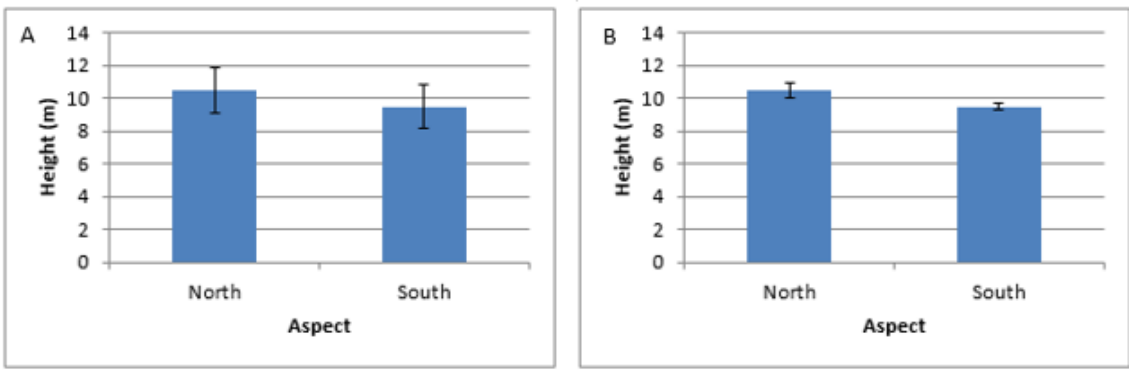



Figure 19. Mean +/- standard deviation for two hypothetical tree samples. The means are the same, but the samples have different amounts of variation.

**Continued**

**Model Skill: Statistical Testing, cont.**

If the odds of getting samples this different, given that the populations are the same, are less than one in 20 (0.05), we say that the test showed a **significant difference**. If the chance is 0.05 or above, we say that the groups are the same or that there was no significant difference. If you were reporting your findings, you could not say that the north slope trees were taller because it is likely that a sample this small, with this much variation, could be obtained even if the populations were identical. The cutoff of 0.05 is arbitrary, so researchers usually report the P-value obtained from their statistical tests. The smaller the P-value, the less likely it is that the researchers are making a mistake when they infer that the populations are different. For more on statistical tests, see Appendix C.

**Misconception Alert: Statistical significance means importance**

**FALSE.** A statistical test can't indicate whether differences are important. You might find that trees on the north slope are 1 cm taller, on average, than those on the south, and that the difference is statistically significant. The difference may not be biologically important.

Imagine that you wanted to test for habitat preference by a large mammal. You could fit them with GPS-enabled collars and gather data on several individuals, then identify the habitat type of the areas they used (Figure 20).

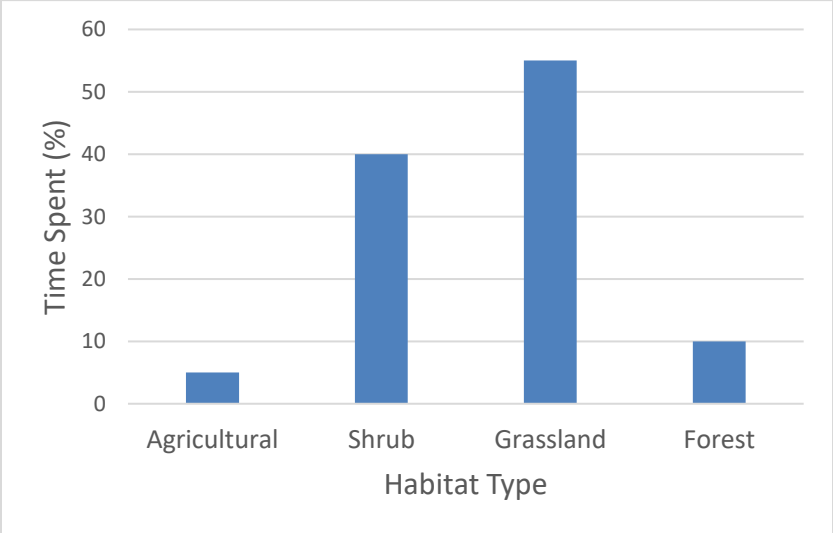



Figure 20. Hypothetical chart of habitat use by a large mammal.

**Analyze the Figure**

- Which habitat did the animals use the most and the least?
- Is it valid to equate their use of the habitat types with preferences?

At first glance, it might seem that the animals prefer grasslands, but what if most of the habitat in the area is grassland? Researchers use models that allow them to compare the movements of the animals to what one would find if animals were moving randomly through the environment. In other words, if 65% of an area is grassland, and animals were moving randomly, we would expect to see them in grassland roughly 65% of the time. To make inferences about preference, we must be able to compare use with availability (Figure 21).

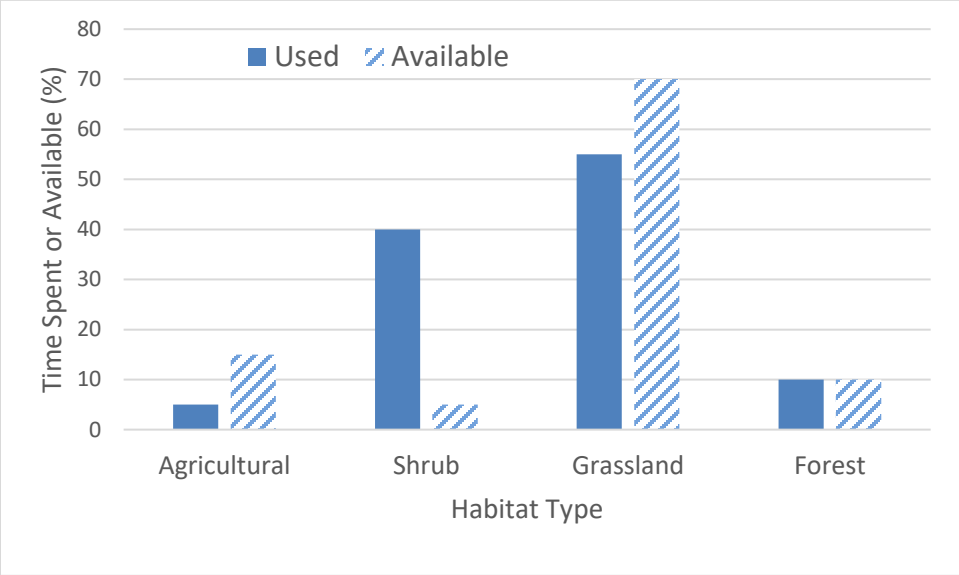



Figure 21. Hypothetical chart on habitat use by a large mammal and habitat availability in the same area.

**Analyze the Figure**

- Which habitat did the animals use more than they would if they were moving randomly?
- Which habitat do they seem to be avoiding?

It would still be necessary to test whether the differences between availability and use were statistically significant. Even if the differences were significant, it might not be the whole story. It's common to see differences in habitat preference during different seasons, at different times of day, or in years with different levels of food availability. Habitat preferences may differ between sexes and change with age and condition. For a discussion of how habitat preference might be flexible, see **Taking It Further: Functional Response in Habitat Selection**. Do your own experiments on habitat selection following the instructions in **Do Try this at Home: Habitat Selection**.

**Taking It Further: Functional Response in Habitat Selection**

The variables that drive habitat selection in a species may be resources that the organisms use or threats that they avoid. Sometimes the picture is complicated because the importance of a particular factor may change. For example, individuals may usually avoid an area that has many predators, but this preference may disappear when food is scarce. The change in habitat preference due to environmental changes is a functional response.

Woodland caribou (Figure 22) numbers are decreasing, in part because of activities such as clearcutting in their habitat. Past studies showed that woodland caribou habitat use could be explained in part by the availability of the moss that they eat. But there were conflicting findings about whether the caribou preferred mature (old growth) conifer forest.

**A**

https://commons.wikimedia.org/wiki/File:Woodland_Caribou_Southern_Selkirk_Mountains_of_Idaho_2007.jpg

**B**

https://en.wikipedia.org/wiki/File:Gordon_River_Clearcut.jpg

Figure 22. **A**. Woodland caribou (*Rangifer tarandus*). **B**. Clearcut in a conifer or boreal forest.

Moreau et al. (2012) wondered if this were due to a functional response based on how much of the landscape had been clearcut. They used radio collars to track caribou with satellites and found that in areas with little clearcutting, caribou chose sites based on food. In areas with more clearcutting, caribou selected sites that had more mature conifer trees. This was true on two scales. Across landscapes with more clearcuts, caribou were more common in mature forests. Within individual caribous' home ranges, they were more likely to be in patches of old growth forest. This information may be critical in managing caribou and making land use decisions.

To learn more, see: Moreau, G., Fortin, D., Couturier, S., & Duchesne, T. (2012). Multi-level functional responses for wildlife conservation: the case of threatened caribou in managed boreal forests. *Journal of Applied Ecology*, *49*(3), 611-620.

**Do Try this at Home: Habitat Selection**

http://commons.wikimedia.org/wiki/File:Embracing_the_isopod_(3506396489).jpg

Figure 23. Terrestrial isopod.

Animals can use behavior to move to a better microclimate. If you live in a temperate climate, you can probably find soil isopods under rocks (Figure 23). These crustaceans are known as rolly pollies, pillbugs, wood lice, or sowbugs (though true sowbugs cannot curl up). They are not insects. They breathe through gills that must be kept moist, so they need to find cool, damp microhabitats.

It is not necessary for the pillbugs to know that they need these habitats, they just need a couple of simple movement rules. One is “travel more in dry habitats.” This keeps them in moist places and moves them out of dry places more quickly. Another rule is “travel away from the light.”

If you provide habitats that differ in their light and humidity, you can watch these behaviors. Any container about the size of a plate will do for a testing area. A sheet of plastic wrap will keep in animals and moisture while you view them. Put a moist paper towel in to keep the animals from drying out. You can cover one half and time where individuals tend to be. You can provide different moisture levels. When the animals stop moving, you need to put them back in a moist place.

**Check Your Understanding**

- Why might an animal go to a habitat that is not optimal for it?
- How does habitat selection shape the range of a species?

**Case Study Part 3: Risks to Wildlife**

When a pathogen is found for the first time, it is almost impossible to know whether it has been around a long time, but was just discovered. It is also possible that the disease was present, but not very common. Perhaps the hosts were able to fight off the disease in the past, but they are under more stress now because of changing climate or lower food levels. If the disease is actually new, that may pose the biggest risk because the immune systems of the hosts did not evolve along with this threat.

Researchers tested whether fleas reduced the ability of Ross's geese and snow geese in Nunavut, Canada to successfully raise young. Fleas drink the blood of the animals they live on. A few fleas may not reduce an animal's fitness, but larger infestations could. In addition to sucking blood, fleas carry diseases. Instead of trying to count fleas on the birds, researchers measured the percentage of goose eggs that had blood on them. A goose with more flea bites would probably get blood on more eggs. They also measured reproductive success and found that the two were inversely correlated, but that the effect was small. Geese leave the nest early, potentially limiting the damage done by fleas.

Fleas could also reduce the long term health of the geese. Perhaps even the successful geese had to use up their energy reserves to raise their offspring. This could make the geese more vulnerable to predators, disease and starvation. As temperatures rise in the Arctic, more fleas may survive the winter.

By Andrew C - Ross's Goose (Chen rossii), CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=55313907

https://commons.wikimedia.org/wiki/File:Lesser.snow.goose.white.arp.750pix.jpg

Figure 24. Ross's goose (*Chen rossii*) and lesser snow goose (*Chen caerulescens*).

**Learning from the Case Study**

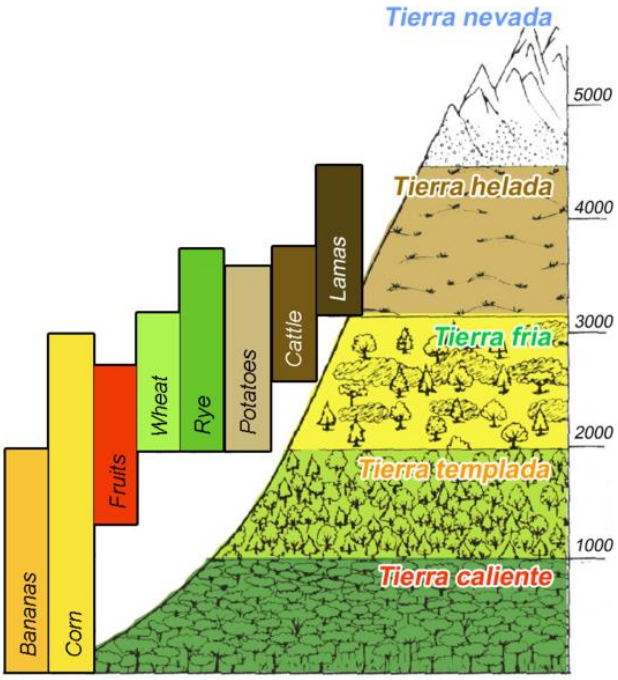
- How do the concepts of range and habitat explain how some diseases may become more of a threat?
- How can expansion of the range of one species influence the range of other species?

# Key Concepts

- A habitat provides suitable living conditions and resources for a species. It may be marginal, optimal, or somewhere in between.
- Species ranges and distributions are determined by abiotic factors or by other species.
- Species ranges can shrink or grow due to changes in habitat or biotic factors
- Local distribution patterns vary between species
- Organisms can select habitats on short or long time scales, but decisions are not always optimal.

# Apply the Concepts

1. *Apply concepts of habitat, range, distribution, and habitat selection to describe where species are found*
2. *Draw reasonable conclusions about how biotic and abiotic factors influence range*
3. *Explain why the size of a species' range may shrink or grow*




http://en.wikipedia.org/wiki/File:Hoehenstufen_der_anden.en.PNG

Figure 25. Ranges of crops and livestock raised in the Andes Mountains of South America. Elevation is shown in meters.

1. Refer to figure 25.

A. Why would the plant community at high elevations be different from the plant community at low elevations? Describe a few abiotic factors in your answer. *(Learning Outcomes 1 & 2)*
B. Why would the animal species be different in the different zones? Describe both abiotic and biotic factors in your answer. *(Learning Outcomes 1 & 2)*
C. Do you think that bananas could be grown at 3000 m? Discuss your assumptions in your answer. *(Learning Outcomes 1, 2 & 3)*

2. How could natural selection lead to a species becoming able to invade marginal habitat? For example, how might a low elevation plant species eventually adapt to invade higher elevations? [Hint: avoid misconceptions about natural selection and evolution.] *(Learning Outcomes 1, 2 & 3)*

3. Sometimes development is planned for areas that contain threatened or endangered species. One potential solution would be to move the species to a new area. What are some of the possible issues to consider when moving species? *(Learning Outcomes 1, 2 & 3)*

4. If researchers find that an insect species is often in a particular habitat, does that mean the habitat is optimal or that the insect selects that habitat? Explain your answer. *(Learning Outcome 1)*

5. What traits might make a non-native species invasive? *(Learning Outcomes 1, 2 & 3)*

6. If you find that aspen trees tend to grow in clumps, what are some potential explanations for this pattern? *(Learning Outcome 1)*

# Unit IV

# Populations

Burton 2013

Baby tortoise and egg in a reserve in Galapagos National Park, Ecuador. Markings tell where and when the egg was laid. The egg must be kept with the markings facing up.

**Living things have characteristic patterns of behavior, reproduction and life span, which shape their population patterns.**

**Unit Outcomes**

- Use concepts and mathematical models to accurately describe, explain, and predict changes in population size
- Effectively analyze interactions between members of the same species
- Accurately explain how the environment influences patterns of reproduction and lifespan in different species

**Unit IV: Populations**

# Chapter 11: Living in a Population: Behavior and Evolution

## Case Study Part 1: The Enemy You Know

**A**

Ian D. Wilson,
https://commons.wikimedia.org/w/index.php?curid=1214891

**B**

https://mdc.mo.gov/discover-nature/field-guide/red-winged-blackbird

**C**

https://en.wikipedia.org/wiki/Red-winged_blackbird#/media/
File:Red-winged_blackbird_versus_osprey_4.jpg

Figure 1. A. Red-winged blackbird (*Agelaius phoeniceus*) male, B. Female with nestlings, C. Male mobbing an Osprey (*Pandion haliaetus*).

Red-winged blackbirds on a spring day seem to demonstrate cooperation in a **population**. Males are spaced fairly evenly along the edges of a marsh or a wet roadside trench. They sing from conspicuous perches. Females and their young are hidden nearby. An Osprey flies over. It may be a threat to eggs or young birds. The males mob the larger bird, diving at it and chasing

it, apparently ignoring their own safety. But are the birds really putting the needs of their fellow blackbirds ahead of their own?

Let's start by analyzing the apparent family. It seems likely that the male is guarding his mate and their offspring, but the young in the nest may not be his own. In the 1970's researchers vasectomized (sterilized) all the males in a population of the birds to study possible ways of controlling Red-winged blackbird populations. They found that nearly half of the nests guarded by the vasectomized males contained at least one fertile egg. Biologists knew that male Red-winged blackbirds would mate with any female if they got the chance, and a male might have two or three females on his territory, but they were still surprised that so many females were mating with males other than their apparent mates. This chapter will examine the relationships between members of populations and how individual fitness shapes populations and mating systems.

As you read about the behavior of animals (or other organisms) in this chapter, you may be tempted to make value judgments or to interpret the behavior as if the individuals had the same motivations, emotions, or thought processes as humans. This is called **anthropomorphism** and should be avoided. It can interfere with your ability to think analytically about the fitness values of behaviors.

**Learning from the Case Study**

- Why would it be surprising for individuals to sacrifice themselves for other individuals in the population?
- Why might a female benefit from mating with males other than her apparent mate?
- Why does it benefit a male to guard a female and offspring even if the female is mating with other males?

# Learning Outcomes

1. *Accurately explain causes and effects of intraspecific competition*
2. *Accurately describe how conspecifics can benefit each other*
3. *Effectively evaluate the influence of various mating systems on individual fitness*
4. *Accurately analyze how relatedness influences unselfish behavior*

**Vocabulary Toolkit**

**Roots**

Mono = one
Poly = many
Gyno = female
Andro = male
Eco = household

**Word Watch List**

**Population**: All members of the same species in a given location
**Anthropomorphism**: Attributing human emotions or motivations to non-humans
**Conspecific:** Member of the same species
**Intraspecific competition**: Competition (attempted use of the same resources) between conspecifics
**Foraging**: Process of gathering resources, such as food
**Scramble competition**: Competition focused on resource use rather than direct interaction with competitors
**Territory**: Area an individual or social group will defend from conspecifics
**Interference competition**: Competition that involves attempting to directly stop competitors from using resources. It may involve fighting or chemicals
**Opportunity cost**: A tradeoff in which time or other resources spent on one activity are not available for other activities
**Optimal**: Best possible, with highest ratio of benefit to cost
**Monoecious**: Having both male and females structures in one individual
**Polygynous**: A mating system in which one male mates with multiple females
**Polyandrous**: A mating system in which one female mates with multiple males
**Monogamous**: A mating system in which one female mates with one male
**Extra-pair copulation**: Mating between an individual that is part of an apparent pair and an individual other than the social mate
**Altruism**: Sacrificing individual fitness for other individuals
**Kin selection**: Process in which an individual's genes are passed by its relatives
**Relatedness coefficient (*r*)**: Number used to describe the probability of two individuals having the same allele at a given locus. For identical twins, it is 1

## Individuals Compete with Conspecifics

**Populations** are groups of individuals of the same species in the same place and time. Aside from a few special cases, natural selection happens at the level of the individual. If the individual reproduces, it passes on copies of its DNA. Recall from Chapter 4 that the number of copies of its DNA that it passes along compared to other individuals in its population determines its fitness. Members of the same species—**conspecifics**—usually need the same resources and use the same habitats. This means that members of the same population are potential competitors. Competition between conspecifics—**intraspecific competition**—can be greater than competition between members of different species.

**Misconception Alert: Natural selection acts for the good of the species**

**FALSE.** Natural selection is the result of individuals leaving more offspring than other individuals within a group of the same species. Individuals may increase their fitness in many different ways, which will vary by the species. They might invest more in their offspring, cooperate effectively, fight off disease better, be better at infecting other organisms, conserve water better, or attract better mates, for example.

Crowded plants block each other's light and use water and nutrients, potentially making them less available. Physical space itself can be limited. Researchers grew mouse-ear cress (Figure 2) under different densities to determine whether crowding decreased individual reproduction or growth (Figure 3). The plant produces seed pods, so these were counted to determine reproductive output.

http://en.wikipedia.org/wiki/Arabidopsis_thaliana#/media/File:Arabidopsis_thaliana.jpg

Figure 2. Mouse-ear cress (*Arabidopsis thaliana*).

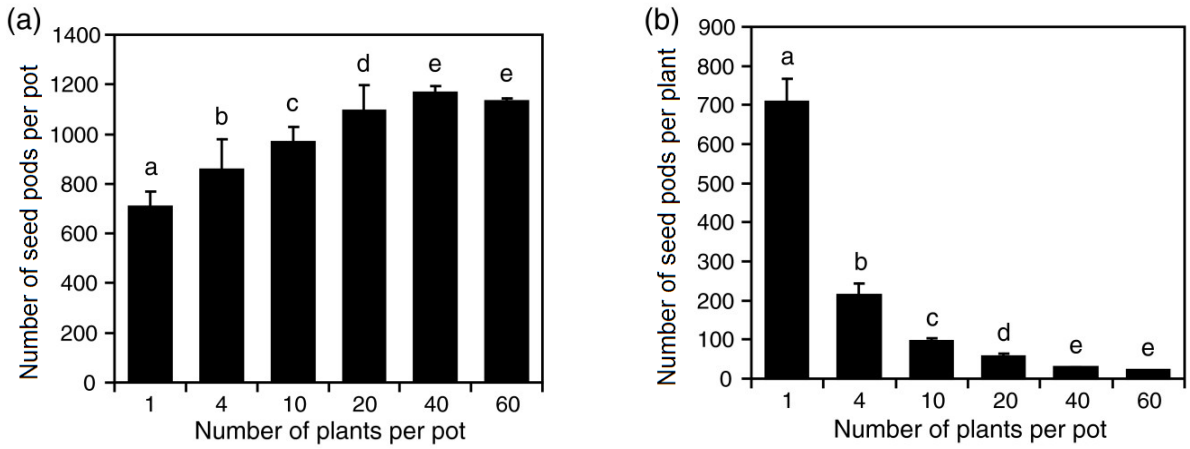



Figure 3. Mouse-ear cress (*Arabidopsis thaliana*) reproductive output in number of seed pods per pot (a) and number of seed pods per plant (b) and different plant densities. Letters indicate whether there is a significant difference between treatments. If bars have the same letter, there is no significant difference between them. Modified from: Masclaux, F. G., Bruessow, F., Schweizer, F., Gouhier-Darimont, C., Keller, L., & Reymond, P. (2012). Transcriptome analysis of intraspecific competition in Arabidopsis thaliana reveals organ-specific signatures related to nutrient acquisition and general stress response pathways. *BMC plant biology*, *12*(1), 227.

**Analyze the Figure**

- How did the density of plants influence reproduction per pot?
- How did the density of plants influence reproduction per plant?
- Did intraspecific competition reduce the fitness of individuals in this study? What is your evidence for this conclusion?

Notice the difference in how one could interpret the results. If you were a farmer interested in maximizing seed pod production, you might want the plants to be crowded, at least to the 40 plants per pot level. However, the individual fitness of the plant is highest at the lowest density. For a discussion of management implications of these patterns, see: **Why It Matters: Intraspecific Interactions are Critical to Conservation**

Animals compete for space, food, and other resources. Researchers in Britain and Ireland studied how intraspecific competition in Northern gannets (Figure 4) influenced the amount of time and effort the sea birds needed to get fish to feed their nestlings (Figure 5). The birds nest in large colonies along the coast but do all their **foraging** for food in the sea nearby.

http://commons.wikimedia.org/wiki/File:Northern-Gannet-13.jpg

Figure 4. Northern gannet (*Morus bassanus*) carrying nest material.

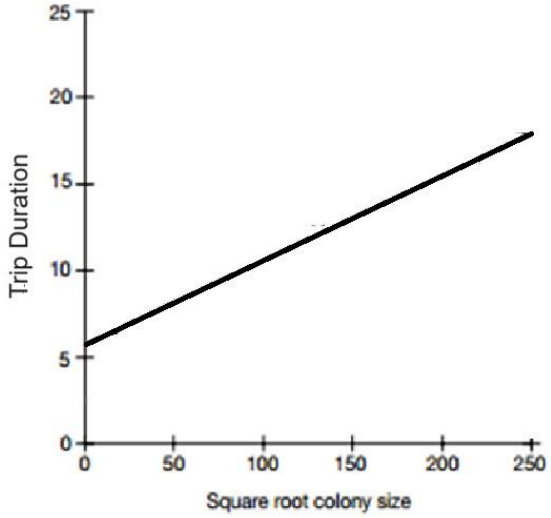



Figure 5. The influence of number of birds (square root colony size) on how long it takes Northern gannets (*Morus bassanus*) to find fish. Modified from: Lewis, S., Sherratt, T. N., Hamer, K. C., & Wanless, S. (2001). Evidence of intra-specific competition for food in a pelagic seabird. *Nature*, *412*(6849), 816-819.

**Analyze the Figure**

- What is the general pattern in the graph?
- How would you explain this relationship?
- Why might researchers have used trip duration to measure foraging effort?

Researchers found that population growth was lower in years when colony size was large. How would you explain this finding? Chapter 12 will discuss changes in population size in more detail.

How can an individual reduce the cost of neighbors using resources it needs? Individuals of any species may try to use resources before other individuals, whether they are conspecifics or not. This is **scramble competition**.

Recall from Chapter 10 that a home range is the area where an individual is usually found. It is not defended. Some animals defend a portion of their home range. The defended part is a **territory**. Defending a territory is a type of **interference competition** in which individuals try to prevent others—whether they are conspecifics or not—from accessing a resource. Defending a territory has costs. Animals spend time and energy patrolling the boundaries of their territories, communicating threats to conspecifics, and possibly fighting. Fighting also creates a risk of injury, even for the winner. Animals may use a variety of signals that an area is being defended (Figure 6). These could be chemical (such as marks from urine or glands), visual (such as scratches on trees or objects left on occupied dens), or auditory (such as howling or singing). While these signals are less costly than actual fighting, they take time and energy and can make an individual obvious to predators. Plants or other sessile organisms may use chemicals to interfere with other individuals, which can also be costly.

**Misconception Alert: Animals must know why they are doing something**

FALSE: Animals do not have to know why they do anything. If having a particular gene makes a particular behavior more likely, and that behavior increases an individual's fitness, the gene is likely to become more common in future generations. The fitness value of the behavior is important. There is no need for the individual to understand the fitness value.

**A**

http://ar.wikipedia.org/wiki/#/media/
File:Lobo_marcando_su_territorio-2.jpg

**B**

http://en.wikipedia.org/wiki/Howler_monkey#/media/
File:Howler_monkey.jpg

**C**

http://en.wikipedia.org/wiki/Bird_vocalization#/media/
File:Solsort.jpg

**D**

http://en.wikipedia.org/wiki/Dactyloidae#/media/
File:Green_anole.jpg

Figure 6. **A**. Wolf (*Canis lupus*) marks territory with urine. **B**. Howler monkeys (*Alouatta caraya*) call. **C**. A male blackbird (*Turdus merula*) sings on a high perch that also makes him visible. **D**. Male Carolina anole (*Anolis carolinensis*) signals to other males with a throat pouch display.

Some species are territorial only under some circumstances or in specific seasons. Many animals are not territorial at all. The balance of costs and benefits determines whether defending a territory will increase an individual's fitness. Some resources are difficult to defend. For example, an antelope needs to eat a huge amount of plant material. It could not possibly defend that entire area and still have time to eat. It is better off using scramble competition—trying to eat the best or most plants before its conspecific does, than to spend its time chasing conspecifics away. However, male antelope may defend territories during the mating season, chasing other males away from females. Females stay together as they move to new feeding grounds, so he just needs to defend the area they are in. This defense also has a cost, but the payoff of mating is very large.

**Why It Matters: Intraspecific Interactions are Critical to Conservation**

Yellowtail damselfish (Figure 7A) live in the tropical western Pacific Ocean on coral reefs off the coasts of islands, and perhaps some continental coasts. They have a strong preference for the coral *Acropora* when it is growing in a bottlebrush shape (Figure 7B). Juveniles tend to stay in groups.

**A**

http://commons.wikimedia.org/wiki/File:Blue_Fish_(8030224092).jpg

**B**

http://coral.aims.gov.au/factsheet.jsp?speciesCode=0835

Figure 7. **A**. Damselfish (*Chrysiptera parasema*). **B**. The bottlebrush growth form of a species of coral (*Acropora navini*).

Coral reefs are threatened by increased water temperature, water pollution, over-fishing of species that protect reefs, and other factors. This makes the study of reef species more urgent. Researchers decided to study the effect of crowding fish onto the smaller reefs to determine whether shrinking reef sizes will cause reef fish populations to decline. One hypothesis was that crowding might help the fish because predators might eat the same number of damselfish, but this would be a smaller proportion of the damselfish population. Another hypothesis was that the damselfish might fight more, causing more mortality. Competition for food or shelter could also make crowding a problem.

The researchers measured juvenile fish mortality (death rate—this concept will be discussed further in Chapter 13) at different starting densities of juvenile damselfish on a coral reef in Papua New Guinea (Figure 8).

**Continued**

**Why It Matters: Intraspecific Interactions are Critical for Conservation, cont.**

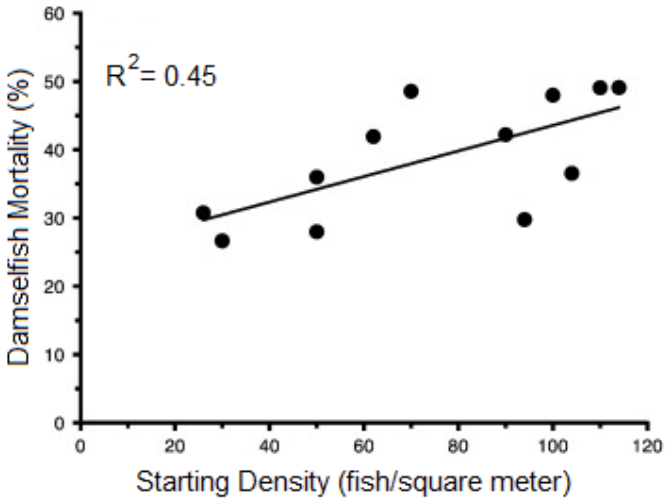



Figure 8. Influence of the starting density of fish on fish mortality. Modified from: Boström-Einarsson, L., Bonin, M. C., Munday, P. L., & Jones, G. P. (2013). Strong intraspecific competition and habitat selectivity influence abundance of a coral-dwelling damselfish. *Journal of Experimental Marine Biology and Ecology*, *448*, 85-92.

**Analyze the Figure**

- What is the general effect of starting density on mortality?
- Using the trend line, calculate which starting density would have the greatest ending density of damselfish per meter. [Hint: The number that died is the starting number of fish multiplied by the mortality. Subtract the number that died from the starting density to get the number that lived.]

Damselfish were not fighting much in this study, nor were they crowded out of shelter, but less food may have been available. Parasites and diseases may also have increased mortality. Other studies have shown that yellowtail damselfish grow more slowly when they are crowded, making them more vulnerable to predators, and decreasing their reproduction.

- How does understanding the effect of individual damselfish on each other help in the management of coral reefs?
- How might the survivorship data be used differently by people who are interested in coral reef conservation and those who have a stake in continuing activities that damage coral reefs?

**Case Study Part 2: Why Are The Males Singing?**

Singing is a serious business. Male Red-winged blackbirds arrive in potential mating grounds before the females. There is intense competition between the males for the best habitat patches because females will be choosing these patches soon for their own nesting area. A male with a very good territory may be able to attract 2 or even 3 females to his territory. As the territories are set up, there may be actual fighting. After territories are established, the males use singing alone to retain territories and actual fighting is rare.

Singing for hours a day takes energy. Any time and energy that an animal spends defending its habitat is time and energy that it is not spending on other activities, such as foraging for food. The total of the resources—such as time and energy—used for one activity at the expense of another is the **opportunity cost** of an activity. If an animal can eat while it defends its territory, for example, the opportunity cost of territory defense is lower than if the animal can only do one activity at a time. This makes the singing an honest signal. Either the male can spend hours a day singing without feeding, exposing himself to predators, or he cannot. There is no way for a weak male to cheat.

**Learning from the Case Study**

- What are the costs of singing?
- Why wouldn't a weak male ignore the singing and still try to take over a male's territory?
- Why would fighting decrease as the territories are established?

**Model Skill: Optimality**

Fitness for an individual increases when it reduces its costs and increases its benefits, but the relationship between these variables is not always straightforward. Consider a resource such as food. An individual animal requires some minimal amount to stay alive. More food allows an individual to heal, grow, have an immune response, and store the excess. There is some minimum amount of food intake needed for an animal to reproduce. But there can be too much of a good thing. If an animal puts on too much fat, its travel costs increase and its health may decline, so the benefits of eating a lot can be less than the benefits of eating a bit less. There is an **optimal** level of food intake that results in the highest evolutionary fitness (Figure 9).

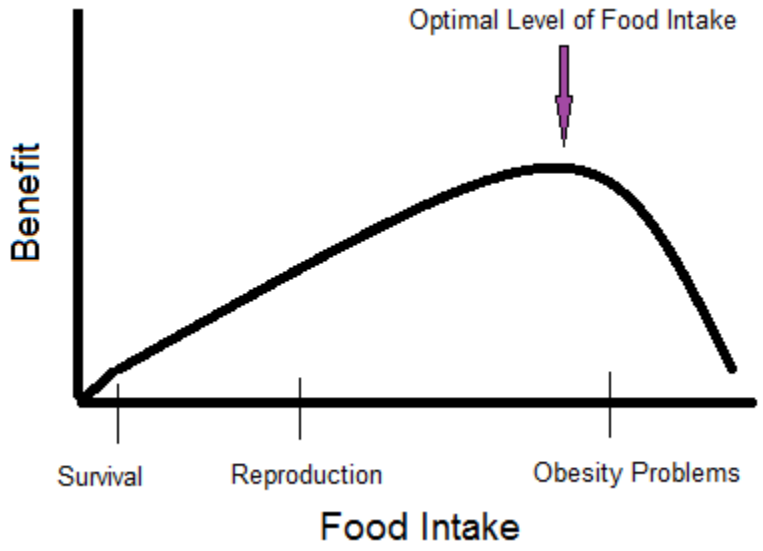



Figure 9. Hypothetical optimal level of food intake (purple arrow) is not the maximum food intake, it is where benefits are highest.

**Analyze the Figure**

- Is the maximum level of food intake the same as the optimal level of food intake?
- Why might the benefit curve for a different activity have a different curve?

So far, we have only discussed the level of benefits. There is usually a cost to obtaining food. If that is added to the model, the optimum food intake level may change (Figure 10). The cost of obtaining each food item could be the same. This is represented by the dashed red line.

**Continued**

**Model Skill: Optimality, cont.**

The optimal level of food intake would be at the point where the net benefit (benefit – cost) is the greatest. In this model, the optimal level (shown with the blue arrow is the same as it was in Figure 9. The possibility that food will get more and more costly to obtain as the close, obvious, and easily accessed food is used up is represented by the solid red curve. In this model the optimal level of food intake is greatest at a much lower level. (To measure the difference between cost and benefit for yourself place the zero line of a ruler on the cost curve and slide it so that you can read the distance between the cost and benefit lines at multiple points. The optimal point is where this distance is the greatest.)

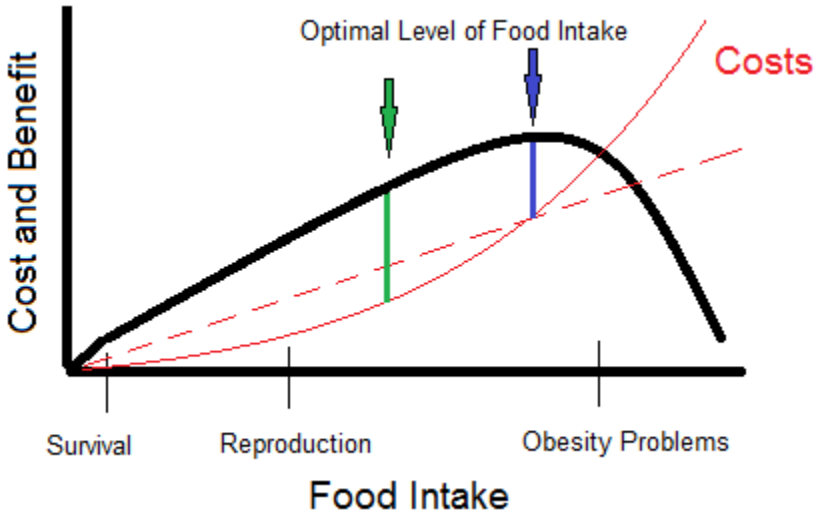



Figure 10. Costs and benefits of different levels of food intake. The dashed red line indicates that each food item has the same cost. The blue arrow indicates the optimal level of food intake in this model. The solid red curve indicates that food gets more costly to obtain as more is consumed. The green arrow indicates the optimal level of food intake in this model.

**Analyze the Figure**

- Why is the optimal level of food intake different depending on the assumption of the cost?
- Describe conditions where each cost curve seems more realistic. For example, is there likely to be a difference between grazing antelope and owls that are flying around their territory hunting mice?

The optimal territory size is determined by the benefits gained from exclusive use of the territory and the costs of defending it (for more on this concept, see **Model Skill: Optimality**). A larger territory will probably contain more resources, but it will also cost more time and energy to defend (Figure 11). A higher-quality habitat will contain more resources per unit area (greater benefit for the same cost), so the optimal territory size will depend on the quality of the habitat.

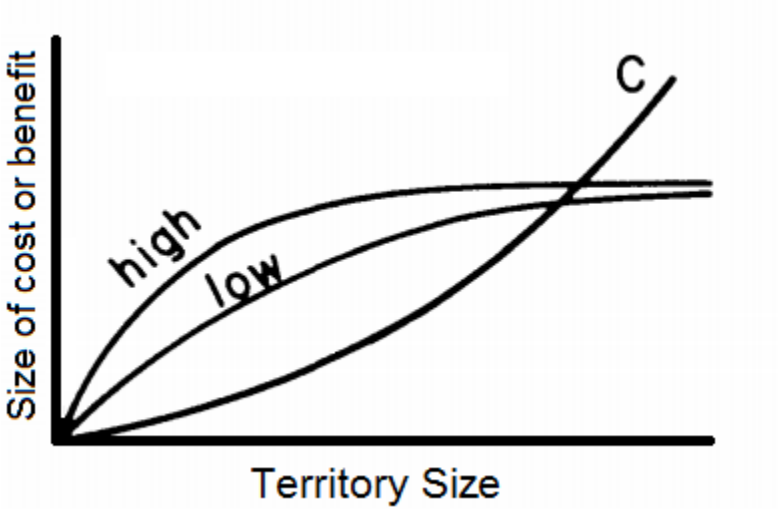



Figure 11. How costs and benefits of territoriality change as territory size changes. C = cost. The labels "high" and "low" on benefit lines refer to the quality of the territory. Modified from: Schoener, T. W. (1983). Simple models of optimal feeding-territory size: a reconciliation. *American Naturalist*, 608-629.

**Analyze the Figure**

- Is the optimal territory size for a high-quality habitat the same as for a low-quality habitat?
- Does the cost of defending a territory increase in a straight line in this model, or does it get more and more expensive to defend the same additional area?
- Why would the benefit of a larger territory level off? Why does it level off more quickly in a high-quality habitat?

In this case, the optimal territory size (benefit – cost) is slightly larger in the low-quality territory. Once the animal has plenty of food, there is little benefit to having a larger habitat, and this size will be reached earlier on a high-quality habitat. The cost of defending a territory increases faster as the territory size increases because of the direct cost and the opportunity cost. The animal has to spend a larger and larger portion of its time on territory defense. The larger a territory is, the less likely it is that an animal can defend it at the same time it is doing other things.

Animals may not use territoriality to claim resources. They can also use dominance. For example, an antelope can force other antelopes from a good patch of food. If the same

individuals live together, they might learn which individuals they can defeat and which can defeat them, this creates a dominance rank. When each individual knows its rank, it can avoid risk and wasted energy by letting dominant individuals take resources.

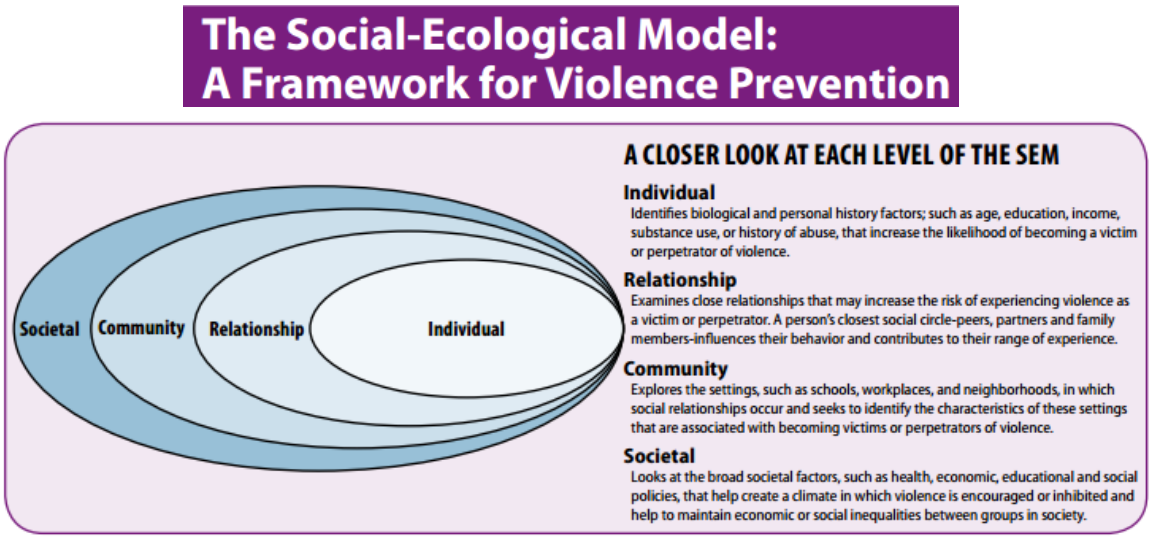
If individuals cannot remember interactions, or if they do not live with the same small group all the time, they may need to establish dominance each time they meet. If one individual can clearly tell that it is not going to win, it would do best to just avoid the interaction. Closely matched individuals might use displays to figure out which one is dominant, but they may also need to fight. Stag beetles (*Lucanus cervus*, Figure 12) live in the southern part of Britain. Males fight over food and females. First they display their antler-like head appendages. One may be convinced he's smaller and retreat. This saves him energy and the risk of injury. If neither backs down, each will attempt to flip the other.

https://commons.wikimedia.org/wiki/File:Stag%27_beetle_fight._Barbate_salt_marsh._April._1975_%2837498383270%29.jpg

Figure 12. Male stag beetles assess each other. If they are similar in size, they may fight until the winner throws the loser off the branch or onto its back.

Fighting between non-human animals is usually a way to get or defend resources such as space, food, or mating opportunities. When the cost of fighting is greater than the benefits, fighting reduces an individual's fitness. For a discussion of violence in humans, see **Make the Medical Connection: Violence and relatedness.**

**Make the Medical Connection: Violence and relatedness**




http://www.cdc.gov/violenceprevention/pdf/sem_framewrk-a.pdf

Figure 13. CDC violence prevention model.

What causes violent behavior between humans? Homicide is the most extreme case of violence between individuals. According to the US Federal Bureau of Investigation, over 14,000 homicides occurred in the United States in 2013. An FBI report of statistics from 1980 to 2008 showed that over 90% of the killers and 77% of the victims were male. Young adults (18-24 years) were the most likely victims of homicides. For victims under the age of 5, the killer was a parent in 63% of cases. Only 3% of the killers of young children were strangers.

The US Centers for Disease Control recognizes violence is a public health threat. The CDC tracks many risk factors, including age and gender of victims and perpetrators and any known relationship between victim and killer. The CDC has developed a social-ecological model to understand and reduce violence.

**Check Your Understanding**

- Why might intraspecific competition be more intense than competition with individuals of other species?
- How might density influence fitness of individuals?
- Discuss the costs and benefits of defending a territory.
- Why wouldn't a smaller weaker individual challenge the dominant individual in a dominance rank system?

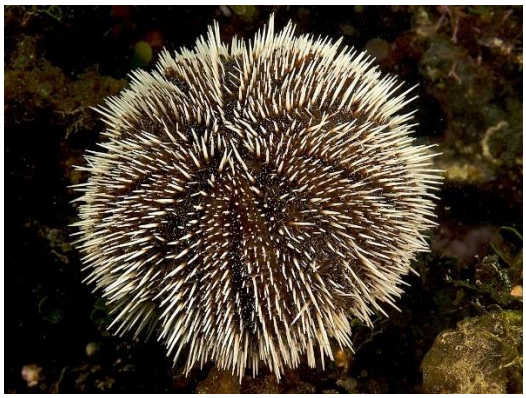
**Mate Competition and Mate Selection Influence Fitness**

Individuals may need to compete with each other for mates or they may need to select between the available mates. Mating systems depend on what each sex brings to the process of reproduction and on the environment. Some species shed their gametes into the environment. For example, pine trees shed their pollen (which contains sperm) into the wind and sea urchins shed their eggs or sperm into the water (Figure 14). Usually, the more pollen that falls on the female structures of conspecifics, the more fit this pine tree will be. It cannot direct the pollen or choose the trees that are pollinated. Like the pine tree, the urchin cannot direct where the gametes go. This results in a scramble competition between gametes of the same type (eggs competing for the best sperm, sperm competing for access to eggs). The physiology of these individuals is under selection to optimize the timing of when they shed their gametes, how much they invest in each gamete, and how many they produce. Investment in offspring will be discussed more in Chapter 13.

**A**

https://commons.wikimedia.org/wiki/File:Pollen_from_pine_tree_2.jpg

**B**



By Nhobgood Nick Hobgood (original photograph), Papa Lima Whiskey (derivative edit) - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=11788043

Figure 14. **A**. Some plants, like these pitch pine trees (*Pinus rigida*) shed pollen into the air (the cloudy area is pollen being dispersed by the wind). **B**. Many freshwater and marine species, like this white sea urchin (*Tripneustes ventricosus*) shed eggs or sperm into the water.

Some species, like the sea urchin, have separate sexes. Others, like the pine tree, are **monoecious**—each individual has both male and female reproductive structures. Recall from Chapter 4 that the benefit of sexual reproduction is that it produces variation in offspring. So monoecious species usually have mechanisms to stop their own gametes from self-fertilizing.

In some monoecious species, individuals exchange gametes. For example, when earthworms copulate, each gives and receives sperm. In other species, there is competition between individuals to fertilize the other individual's eggs. For example, some flatworms (Figure 15) may spend hours trying to inseminate each other without being inseminated. The losing worm must use its resources to nourish the fertilized eggs, while the winning worm contributes nothing more.

http://en.wikipedia.org/wiki/Penis_fencing#/media/
File:Mating_Pseudobiceros_bedfordi.png

Figure 15. Two monoecious flatworms (*Pseudobiceros bedfordi*) attempting to inseminate each other. The paired white structures are penises. In some species the sperm must be injected. In this species they must just be placed on the other worm in the right general location.

Other species may change sex. Many fish species do not have external genitalia, which simplifies the transition from one sex to the other. Clown fish pairs (Figure 16A) live on a single sea anemone. The larger individual in a pair will become female. This allows the pair to produce more eggs. In other species, such as the blue-headed wrasse (Figure 16B), the largest fish becomes male and monopolizes a group of females. The large male can drive off other males.

**A**

http://en.wikipedia.org/wiki/Ocellaris_clownfish#/media/
File:Anemone_purple_anemonefish.jpg

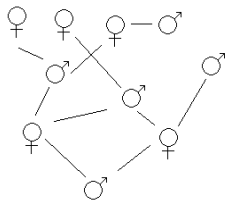
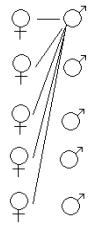
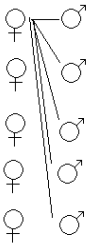
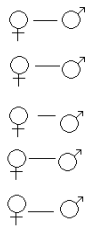
**B**

http://commons.wikimedia.org/wiki/
File:Blue-Headed_Wrasse_(4387352722).jpg

Figure 16. **A**. Clown fish (*Amphiprion ocellaris*). **B**.Blue-headed wrasse (*Thalassoma bifasciatum*). Both species can change sex depending on whether they are the larger fish in the pair or group, but the change is in opposite directions.

In other species, sexes are separate and maintained throughout life. They breed in many different mating systems (Table 1).

Table 1. Mating systems. The lines indicate the primary mating, but there are often other matings. Most mating systems are specific to a species, but in some species the mating system may vary in different environments.

| Type of Mating System | Pattern |
|---|---|
| Scramble<br>Both sexes may have multiple partners. The individuals may come into contact, or they may release gametes into the environment. Success often depends on quality of the eggs and sperm. The effectiveness of anything moving the gametes (pollinators, water currents, wind) can also be important in some species. No social pairing occurs. (Diagram is an example.) |  |
| Polygynous<br>Males copulate with several females, females do most of their copulation with one male. Males provide sperm, but usually no parental care. Males may attract females by holding territories or through displays, or they may keep other males away from the females. Females can all select the best male, so some males will get no mates. Male to male competition is high and some males use alternate strategies to avoid dominant males or coerce females into mating. There may be no social bonds between the males and females. |  |
| Polyandrous<br>Females copulate with several males, but males do most of their copulation with one female. Females may provide little or no parental care but may provide parental care to some offspring. Males can be selective, so some females will get no mates. Female-female competition is high, but not as high as male—male competition in polygynous systems because eggs are more costly to produce than sperm. This pattern is much less common than polygyny. |  |
| Monogamous<br>Females and males form pairs, usually because both are needed to raise offspring. Each individual will usually get a mate, but there is still competition for good mates. Either sex may still copulate with other partners. |  |

Scramble mating systems include the ones described above for individuals that shed gametes into the environment. It also includes species that are not territorial during the breeding season and do not have a stable dominance system. Individuals mate as they get the opportunity (Figure 17). There may still be competition between males, but it is less obvious. For example,

toads may all arrive at the same place at the same time. If a female makes it a bit difficult for a male to grab her, she can eliminate some of the weaker males. If a female mates with multiple males, she will be more likely to have sons with sperm that can out-compete other sperm. Sometimes scramble mating systems are called promiscuous systems, but anthropomorphic language tends to distract people from a valid analysis of fitness costs and benefits.

Dariusz Kowalczyk, https://en.wikipedia.org/wiki/Amplexus#/media/
File:Common_toad_Bufo_bufo_multiple_amplexus_mating_ball.jpg

Figure 17. Common toad (*Bufo bufo*) female with multiple smaller males.

**Polygynous** mating is found in species in which females provide parental care after fertilization and males provide little or nothing except their DNA. In this system, females benefit by choosing males with the best possible genes for her offspring. Of course she does not know this, but females that mate with higher-quality males leave more offspring. This creates selection pressure for females to detect and mate with those males.

Males that copulate with the most females will usually leave more offspring, so there is intense competition between males for access to females. This competition may include male—male fighting, as seen in the stag beetles, or it may involve elaborate physical structures of behavioral displays that include some combination of visual, chemical, and auditory cues (Figure 18). The fewer resources the male provides to offspring, the more elaborate the displays tend to be. Males are unlikely to be selective in their choice of mates in this system. Females are making most or all the investment in offspring, so they will benefit by choosing the best mate possible.

**A**

https://upload.wikimedia.org/wikipedia/commons/4/47/Victoria%27s_Riflebird_courtship_-_Lake_Eacham_-_Queensland_S4E8070_%2822198704599%29.jpg

**B**

http://en.wikipedia.org/wiki/Nyala#/media/File:Fighting_Nyalas.JPG

Figure 18. Polygynous mating systems lead to male—male competition. **A**. Male riflebird (*Ptiloris victoriae*, top) performs an elaborate display while the female (bottom) assesses him. **B**. Two male Nyala (*Tragelaphus angasii*) fight for access to females.

In polygynous systems, a few males get access to many females while most males get few or no mating opportunities. Red deer males, also known as stags (Figure 19) fight each other for access to females. In one study (Gibson & Guinness, 1980), researchers watched individually identified deer for 5 years. They observed the number of females guarded by a particular male on a particular day of the breeding season, multiplied that by the number of fertilizations that happened on that day (calculated by counting back from when young were born), and added up all the days of the breeding season to get an estimate of the number of young fathered by each male. A few dominant stags did almost all the breeding. About 45% of males probably had no offspring, while a few probably fathered 5 or 6. Competing for females by fighting or displaying has both high direct costs and high opportunity costs. Dominant males spend energy and time mating and may be injured or killed. They may stop eating during the mating season and have a decreased immune response but the payoff for being a successful male is high.

http://en.wikipedia.org/wiki/Red_deer#/media/File:Red_deer.jpg

Figure 19. Red deer (*Cervus elaphus*) females (front) and male (back). Males are larger and have antlers used in male-male fights.

Males that cannot out-compete dominant males directly may use alternative mating strategies. For example, cuttlefish can control their color. Smaller males sometimes make half their body look female and direct that side to a larger male looking for mates (Figure 21). They make the side facing the female look male. This can allow them to slip between the large male and the female and transfer their sperm to the female. Other males may merely try to mate with females while larger males are fighting or otherwise distracted. The “sneaky” mating strategies may not result in many matings, but they also cost less. The alternative for non-dominant males is to make a heavy investment in strategies with a low chance of success, or to skip mating entirely.

Observers may be less likely to see the “sneaky” copulations, so genetic testing may be required to get accurate data on which males fathered which offspring. As researchers got access to genetic fingerprinting to determine paternity, they found that behavioral observation and genetic testing gave different results. Male striped plateau lizards (Figure 21) are territorial. However, not all of the eggs laid by females were fathered by the male that holds the territory (Figure 22). Assuming paternity based on how close males and females were to each other throughout the study did not provide a complete picture of the mating system.

http://commons.wikimedia.org/wiki/File:Plateau_Lizard_Sceloporus_virgatus.jpg

Figure 21. Striped plateau lizard (*Sceloporus virgatus*).

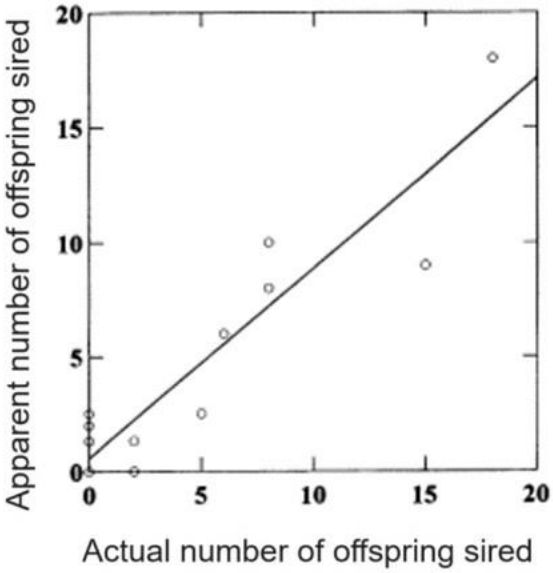



Figure 22. Comparison between apparent parentage inferred by proximity of striped plateau lizards (*Sceloporus virgatus*) and actual paternity determined by genetic testing. Modified from: Abell, A. J. (1997). Estimating paternity with spatial behaviour and DNA fingerprinting in the striped plateau lizard, Sceloporus virgatus (Phrynosomatidae). *Behavioral Ecology and Sociobiology*, *41*(4), 217-226.

**Analyze the Figure**

- Was there a general correlation between the actual number of hatchlings sired and the number that were assumed to be sired by a male based on spatial data?
- Were any males that were assumed to have sired no hatchlings actually successful?

Even in polygynous systems, males do not monopolize access to females. There are still some elements of scramble mating. This should not be surprising because females may benefit from "hedging their bets" by mating with other males. This will increase the variation in her offspring and will protect her from missing a breeding season if the dominant male in the area is sterile or is a poor genetic match for her. She may also have sons with sperm that can compete effectively against other sperm.

In species where a female can lay her eggs and leave them, the mating system may be **polyandrous**. In the yellowtail damselfish discussed earlier, females lay eggs and leave a male to fertilize them, guard them, and fan them with his fins to provide oxygen until they hatch. Female African jacanas (Figure 23A) and spotted sandpipers (Figure 23B) guard territories containing multiple males. The female lays eggs in a single nest at a time, leaving the male to care for the eggs and young. The female is larger than the male in these species, but she does not have the sort of extreme structures or signals seen in many polygynous male birds. In these species, there is also evidence of matings between birds other than the apparent parents.

**A**

By Charles J. Sharp
https://commons.wikimedia.org/w/index.php?curid=53483434

**B**

http://en.wikipedia.org/wiki/Spotted_sandpiper#/media/
File:Actitis-macularia-005.jpg

Figure 23. **A**. Polyandrous African jacana (*Actophilornis africanus*) and **B**. spotted sandpipers (*Actitis macularia*) have multiple males that each raise nests of their eggs.

In species where two parents are needed for the survival of the young, adults form socially **monogamous** pairs. Often this involves displays or paired behaviors that form social bonds between the female and male (Figure 25). These behaviors might involve the individuals demonstrating their fitness by bringing resources (such as food or nesting material), showing off features that advertise their health (such as blue feet) or performing displays that require strength, endurance, or coordination. In monogamous species, males and females usually look very similar because there is very little variation in reproductive success. Each adult needs a mate of the opposite sex, even if the "best" ones are taken, so almost all adults will find a mate unless there is an unequal ratio of males and females.

**A**

By SantiagoGG - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=54373788

**B**

https://upload.wikimedia.org/wikipedia/commons/5/55/Courting_King_Penguins.jpg

Figure 24. Courtship in socially monogamous birds. Blue-footed boobies (*Sula nebouxii*) do a "dance" that shows off their feet. King penguins (*Aptenodytes patagonicus*) do a paired display.

While the pairs are considered monogamous, they may perform **extra-pair copulations** with individuals that are not their social mates. This may be adaptive because a female's social mate may not have the best genes available in the local population. A male may be able to father offspring with multiple females. There is some opportunity cost for a male seeking extra-pair copulations because another male could be copulating with his social mate while he is gone.

### Case Study Part 3: Who Fertilized the Eggs?

If all the male Red-winged blackbirds had been sterilized, what were fertile eggs doing in the nests of half the females? The most likely explanation is that there was at least one male nearby who was not sterilized. He (or they) may have been far enough away to be overlooked or may have arrived later.

When researchers first found out that females had mated with males who were not the male defending their territory, some did not immediately assume that extra-pair copulations were to the females' benefit. Anthropomorphism and their own assumptions about social norms may have influenced their thinking. In fact, females have nothing to lose by mating with a male other than the one guarding the area where she is nesting and may have something to gain. For more on how females may benefit from breeding with multiple males, see **Hypothesis Testing: Does Polyandry Increase Fitness in Female Voles?**

### Learning from the Case Study

- Why would a female mate with males other than the one that guards the territory where she is nesting?

- Why wouldn't a male abandon a nest if the female mated with other males?
- Which males are likely to use alternative mating strategies?

**Hypothesis Testing: Does Polyandry Increase Fitness in Female Voles?**

What does a female gain by mating with multiple males if males give no paternal care? In species where males kill juveniles of their own species, multiple matings may protect juveniles by making paternity uncertain. Males that killed the offspring of their mates would have a low fitness.

Females may also gain a genetic advantage through multiple matings. She might choose the best available male for breeding. If she had mated with one male, then found a better one, she would increase her probability of producing high-quality offspring if she also mated with him. By mating with multiple males, she might protect herself from mating only with a male that would be genetically incompatible with her. She would also increase the genetic variability among her offspring, which could be useful in a changing environment.

A female could influence which male fathered her offspring using behavior, such as allowing different males different mating access. It also appears that she can make physiological adjustments to change the probability of fertilization or invest differently in offspring depending on her mate.

Sperm can compete with each other in a female reproductive tract. Some sperm may swim faster. A male may produce some sperm that attack other sperm, or semen that blocks later fertilization attempts. If a male has sperm with a competitive advantage, his sons may leave more offspring than males with less competitive sperm. This will also benefit his mate, who could also leave more "grandchildren." Providing a competitive situation where the more effective sperm will fertilize more of her eggs would benefit the female.

Bank voles (Figure 26) live in boreal forests. They have a scramble mating system with no paternal care. They breed once a year in the summer.  Females usually mate with multiple males. Controlled tests did not find evidence of females refusing to mate with males based on male rank. Mothers become territorial as they care for their offspring in burrows until weaning (about 3 weeks).

https://commons.wikimedia.org/wiki/
File:Bank_vole_(Clethrionomys_glareolus)_near_Loch_Awe._-_geograph.org.uk_-_1349626.jpg

Figure 25. Bank vole *Clethrionomys glareolus*.

Hypothesis: Female bank voles who mate with multiple males gain genetic benefits.

Klemme et al. (2008) raised bank voles in a laboratory. Each animal had an identifying ear tag. Researchers randomly assigned 30 females to one of two mating conditions: two matings with the same male (monandrous) or two matings, once each with two different males (polyandrous). The same 30 males were used for both treatments.

There were no differences between treatments (monandrous vs. polyandrous mother) in young of the first generation before weaning. In fall, the second generation was weighed (Figure 26A), tagged, and released into outdoor enclosures. Following the harsh Finnish winter, the 41 survivors were live trapped (Figure 26B). All were kept in the lab and reproductive information was gathered on the females. Tissue samples were taken for paternity tests.

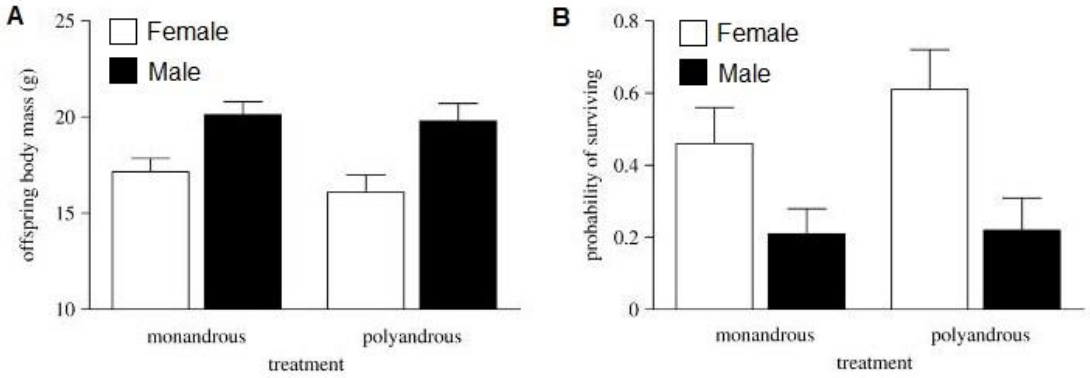



Figure 26. Attributes (mean + std dev) of offspring produced by monandrous (mated with one male) and polyandrous (mated with 2 males) female voles. Offspring body mass was measured in fall. Survivorship probability was measured in spring. Differences between mating treatments were not significant.
Modified From: Klemme, I., Ylönen, H., & Eccard, J. A. (2008). Long-term fitness benefits of polyandry in a small mammal, the bank vole Clethrionomys glareolus. *Proceedings of the Royal Society of London B: Biological Sciences*, *275*(1638), 1095-1100.

**Analyze the Figure**

- How did male and female offspring differ?
- Did offspring body mass or survival vary significantly due to the mating treatment of their mother (monandrous or polyandrous)?

Eighteen litters were produced by the second generation, resulting in 84 members of the 3rd generation (the "grandchildren" of the monandrous and polyandrous females). Researchers analyzed the long-term reproductive success of females in the original treatment (Figure 28). Paternity tests revealed that bigger males had not produced more offspring.

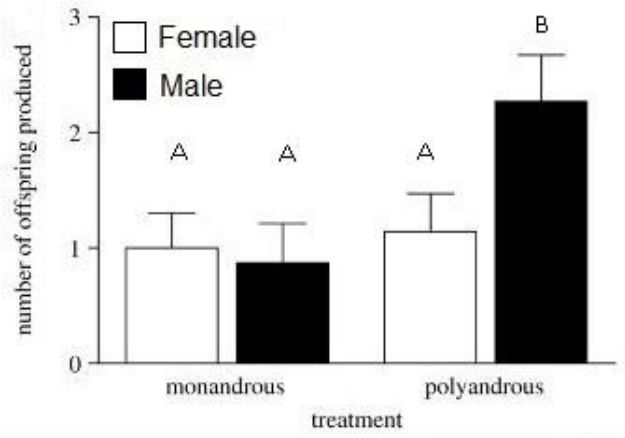



Figure 27. Number (+ Std dev) of 3rd generation offspring produced by the offspring of monandrous and polyandrous female voles. Bars with the same letter were not significantly different. Modified From: Klemme, I., Ylönen, H., & Eccard, J. A. (2008). Long-term fitness benefits of polyandry in a small mammal, the bank vole Clethrionomys glareolus. *Proceedings of the Royal Society of London B: Biological Sciences*, *275*(1638), 1095-1100.

**Analyze the Figure**

- Did polyandrous females have more offspring than monandrous females?
- Did offspring of polyandrous females have more mating success than offspring of monandrous females?

This study shows that potential fitness benefits of mate choice might not be visible in the short term, or the first generation. It does not explain the mechanism of the fitness differences in second generation males, but it is most likely due to sperm competition because second generation females did not have higher fitness.

**Evaluate the Hypothesis**

- Did females gain greater fitness by mating with 2 males instead of one?
- What are some potential mechanisms that could influence a male's reproductive success besides having access to a fertile female?
- What experiment would you do next?

**Check Your Understanding**

- What mating system results in females having the most choice in mates?
- What mating system is likely to result in males that have costly ornaments or displays?
- Why is polyandry not seen in mammals?

## Conspecifics Can Be Beneficial

Being part of a group can help an individual (Figure 29). Prey animals might stay together so that their conspecifics might be eaten instead of them. There are only so many prey that a predator can eat. Groups may also be able to confuse or fight off predators. A group of conspecifics will have a greater chance of spotting a predator than a lone individual. Birds that fly in formation reduce their energy demand. Insects that stay together in cold weather keep each other warmer than they would be alone. Animals that hunt together may be able to kill larger prey. Individuals can watch each other and learn important information, such as the location of food. In all of these examples, each individual may be acting selfishly, but others in the group may benefit as well.

**Misconception Alert: Only unselfish behavior increases the fitness of others.**

**FALSE.** Each individual in a group might be doing things that potentially increase its own fitness while still benefitting others. Note: When ecologists use the term “selfish” they are not making an anthropomorphic judgment about the morality of the individual or assuming the animal knows why it is doing anything. They are merely stating that a behavior potentially benefits the individual.

**A**

By Gordon Firestein - Seacology USA, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=22766988

**B**

http://en.wikipedia.org/wiki/Grant's_zebra#/media/
File:Grant%27s_Zebras,_resting,_Serengeti.jpg

**C**

http://en.wikipedia.org/wiki/Firebug#/media/
File:Pyrrhocoris_apterus_group.jpgview

**D**

http://en.wikipedia.org/wiki/Bird_flight#/media/
File:Lesser_Flamingo.JPG

Figure 28. **A**. Fish can reduce their chance of being eaten if they stay together. **B**. Grant's zebra (*Equus quagga*) often stand in pairs facing in opposite directions. This may allow both an earlier warning when predators approach. **C**. Firebugs (*Pyrrhocoris apterus*) can decrease their energy needs during the cold season by staying together, sharing heat and getting some protection from weather. **D**. Lesser flamingoes (*Phoenicopterus minor*) save energy if they fly together.

Flying in formation reduces the energy used by the birds farther back in the group. The lead bird uses more energy than the other birds. If a bird always led, that would be a form of **altruism**, making a sacrifice for the good of others. So why would a bird lead? If a gene causes an individual to lose more than it gains by being altruistic, we would expect a gene for altruism to die out. But there are ways that altruism actually increases fitness. Birds that fly together generally take turns flying in the lead position. If a bird in a flock of 10 birds does its fair share of leading, it only has to spend about 10% of its time in the lead. A bird that does not take its turn

would probably be avoided by other birds. So taking turns leading will increase a bird's fitness more than trying to cheat and having to fly alone.

This sort of exchange of favors is likely to be common when individuals interact with the same group repeatedly and are able to remember who returns favors. It is also more likely when the cost is small, and the benefit is large. For example, individuals in a group may groom each other, removing parasites. If the animal being groomed doesn't return the favor, the groomer hasn't lost much, but it is unlikely to groom the other individual in the future. For more on this type of interaction, see **Taking It Further: Tit for Tat.**

**Taking It Further: Tit for Tat**

The exchange of favors is also called “reciprocal altruism.” An international competition was held to see who could develop the best computer program for maximizing individual fitness in a series of interactions with the possibility of reciprocal altruism or cheating during a series of interactions. The basis of the contest was a model called “The Prisoner’s Dilemma.”

Imagine that you are a prisoner. You have an accomplice who is being interviewed separately. If you accuse your accomplice, and your accomplice says nothing, you get a large reward. If you say nothing, but your accomplice accuses you, you get nothing. If neither of you says anything you get a moderate reward. If both of you accuse each other, you both get a tiny reward. The game is scored with the different outcomes getting different points (Table 2). If there is only one round of the game each time you play, the highest average payout will be for accusing your accomplice. You will get either 5 points or 1 point. If you stay quiet, your maximum and minimum payouts are both lower (3 or 0). But the game is played as a series of interactions with the same “accomplice.” This would allow either “prisoner” to adapt to what the accomplice did in previous rounds.

Table 2. Matrix of payoffs for the Prisoner’s Dilemma. Modified from: Axelrod, R., & Hamilton, W. D. (1981). The evolution of cooperation. *Science*, *211*(4489), 1390-1396.

| | **Other Person’s Behavior** | |
|---|---|---|
| **Your Behavior** | **Accomplice Stays Quiet** | **Accomplice Accuses You** |
| **You Stay Quiet** | You get<br>3 points | You get<br>no points |
| **You Accuse Accomplice** | You get<br>5 points | You get<br>1 point |

Contestants in a major competition developed many complex strategies that were then played out against each other in computer simulations. The winning strategy was called “Tit for Tat.” The rules of the program were very simple, “start nice, then do whatever the other player did on the last round.” This would be similar to assuming the best about the other individual but quickly punishing them or forgiving them as their behavior changed. Your “accomplice” might still get more points than you, but you will beat others interacting in other pairs. For reciprocal altruism to evolve in a species, we would expect them to be able to detect cheating, punish it, and remember which individuals cheated and which ones reciprocated.

**Case Study Part 4: Why Do Males Mob Predators?**

When the potential predator approached the breeding ground, male Red-winged blackbirds attacked it. How would this increase the fitness of the male? The costs of attacking the Osprey are fairly small. Osprey are a threat to eggs and baby birds but are not likely to injure an adult. By chasing off the potential predator, the male protects his investment in the eggs and young on his territory. They may not all be his offspring, but most probably are. The territories of the males are close together and Osprey fly fast, so all the nests in the area are at risk at the same time. Each male acting selfishly will still result in a group attack on the predator. Attacking as a group is probably more effective than attacking alone, so the Red-winged blackbirds are benefitting from attacking predatory birds with their conspecifics.

**Learning from the Case Study**

- What are the costs and benefits of mobbing a predator?
- Why would a male protect nests that may contain some of another male's eggs?
- Why might attacking the predator increase a male's fitness, even if he were injured?

**Check Your Understanding**

- Describe some ways that cooperating leads to higher individual fitness.
- What characteristics of a species are likely to lead to individuals exchanging favors?

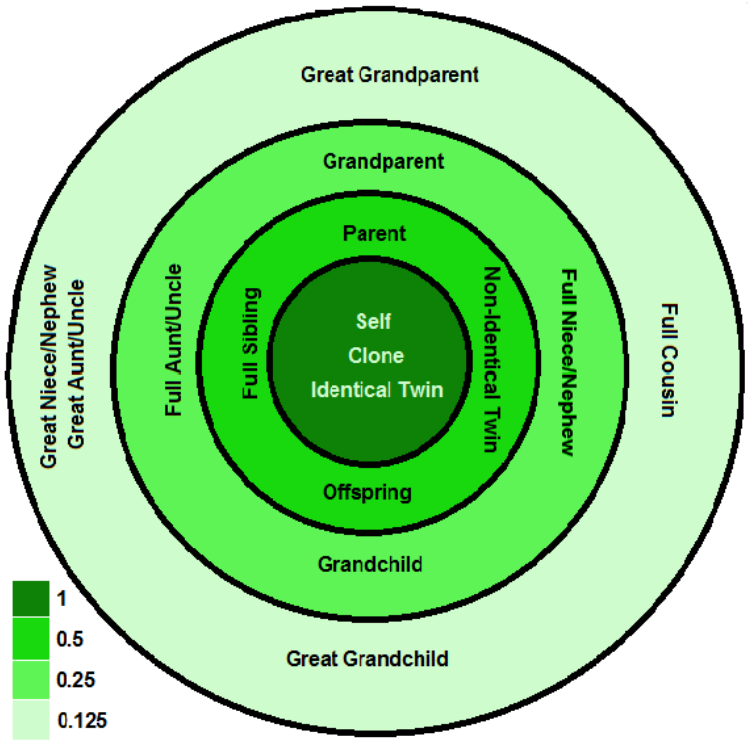
**Helping Relatives Can Improve Individual Fitness**

As mentioned earlier, altruism genes might die out if altruistic individuals had a lower fitness than selfish ones. One exception is when an altruist is helping its relatives. The relatives each have a chance of having the altruistic gene. So even if an individual dies protecting many close kin, the gene for altruism will be passed on. The idea that helping relatives increases the probability of an individual's genes being passed to later generations is called **kin selection**.

The closer the relative is, the more likely it is to share the gene, such as one for altruism (Figure 29). We quantify the level of relatedness as a **relatedness coefficient** (abbreviated as *r*). In diploid species individuals get half their DNA from their mother and half from their father. If a parent has two different alleles (A and B), there is a 50% probability that two offspring got the same allele from that parent (the possibilities are equally AA, AB, BA, BB). There is another allele at that locus from the other parent. If two individuals are half-sibs, the other allele at that locus will be different, so half the alleles at that locus have a 0% chance of matching. This gives half sibs an *r* of 0.25. For full sibs, it's 25% for one allele at the locus and 25% for the other, so the r = 0.5.

**Misconception Alert: An *r* of 0.5 means individuals share 50% of their DNA**

**FALSE.** Individuals in the same species have very little variation in the majority of their genome. Even humans and chimps share over 98% of their DNA. Relatedness coefficients refer to the probability of two individuals sharing the same allele due to shared ancestry. For full siblings, this is 0.5, on average. However, most of their genome will be the same. Genetic fingerprinting is based on the part of the genome that is highly variable between individuals.




Modified from: http://www.flyfishingdevon.co.uk/salmon/year2/social_behaviour/social_behaviour.htm

Figure 29. Relatedness coefficients. Numbers equal probability, on average, of relatives sharing a particular allele, such as one for altruism, at the same locus.

**Analyze the Figure**

- What is the relatedness coefficient between an individual and a full sibling?
- What is *r* for a parent and offspring?
- Is *r* higher for cousins or half sibs?

Most altruism probably is not as dramatic as an individual dying for its family. It could involve giving an alarm call to signal that a predator is near, sharing food, helping to raise siblings, or

allowing a sister's offspring to nurse. These activities have a cost, but it may be low compared to the benefit that the relative receives. For more on how costs, benefits, and level of relatedness influence altruism, see **Evolutionary Perspective: Hamilton's Rule**.

An extreme example of altruism is seen in some species of social insects. Honey bee (Figure 30) colonies usually only have one queen who produces all the eggs. A few males (drones) will fertilize future queens. The rest of the hive—the workers—are sterile females. They forage for nectar and pollen, guard the hive, care for the young, and do all the other work. Why should they do all this work when they won't even reproduce? The queen chemically manipulates the physiology and behavior of the bees in the hive. Kin selection lowers the cost of not reproducing directly. Many of a worker's genes are passed on to the future queens that she helps to raise. There are also reasons why she might be even more closely related to her sisters than her potential daughters, but those won't be discussed here.

By Scott Bauer, USDA, https://commons.wikimedia.org/w/index.php?curid=8339480

Figure 30. Honey bees (*Apis mellifera*) in a hive. The queen (marked with pink by the beekeeper) is in the center.

**Evolutionary Perspective: Hamilton's Rule**

Under the kin selection model known as *Hamilton's rule*, a gene for altruism will remain in a population--or become increasingly common--if an individual helps when:

$$b/c > 1/r$$

Where: $b$ = Benefit to recipient
$c$ = Cost to altruist
$r$ = Relatedness coefficient

This equation can be arranged as $br-c < 0$

To simplify things, assume that there is one gene that causes an individual to be altruistic. In reality, there may be several genes in addition to learned behavior.

If the benefit to the recipient is high, and the cost to the altruist is low, the individuals do not have to be closely related for genes for altruism to be maintained or become more common. For example, a well-fed individual might share food with a relative that is starving. The chance of the altruist passing along its altruism allele has not decreased, but the chance that the relative (who has some probability of having the allele) will live to pass on its allele has increased. If the cost to the altruist is high, and the benefit to the relative is low, the allele for altruism is unlikely to be passed on.

If the relative is distant, the probability that it has a copy of the altruism allele is lower. The cost to altruist would have to be low, and benefit to relative would have to be high, for the altruism to increase the average odds of passing along the altruism allele.

**Check Your Understanding**

- How is kin selection different from altruism between unrelated individuals?
- What characteristics of a species are likely to lead to cooperation between kin?

**Do Try this at Home: Conspecifics and Activity budgets**

Many zoos, museums, and other organizations have video feeds available online so that anyone can study animal behavior from a distance. While you cannot manipulate the behavior of the animals, you can study what they are doing. One technique you can use is to compare activity budgets of different individuals in groups. Using information that you can observe about the animals or read on the web site, you may be able to determine characteristics such as age, dominance rank, sex, or reproductive condition of individuals. You can then compare activity budgets of individuals with different characteristics. You will probably find it easier to complete the study in pairs.

1. Watch the animals for 5 to 10 minutes without trying to record their behavior. You may wish to take some general notes. Decide on types of behavior to record on a checklist (Table 3). Making checkmarks is much easier than trying to write a descriptions of behavior. If working with a partner, make sure you agree on the definitions of your behaviors.

   Table 3. Sample form for recording activities. An actual form would have enough lines to last the entire observation period. The categories of behaviors depend on what is relevant to the animals you are observing.

| Time | Sitting | Grooming Self | Grooming Others | Being Groomed | Eating | Running | | |
|---|---|---|---|---|---|---|---|---|
| 0 | | | | | | | | |
| 10 | | | | | | | | |
| 20 | | | | | | | | |
| 30 | | | | | | | | |
| 40 | | | | | | | | |
| 50 | | | | | | | | |
| (cont.) | | | | | | | | |

2. Develop a plan for systematically collecting data. You might decide to record the actions of the animal once every 10 seconds. One student should observe while the other student takes notes and keeps time. Switch roles after halfway through the observation period. Then repeat the process for another individual

3. Analyze your data to create separate activity budget for your animals. Create a pie chart that shows the proportion of time spent in different activities (Figure 31; see Chapter 7 for more on pie charts).

**Continued**

**Do Try this at Home: Conspecifics and Activity Budgets, cont.**

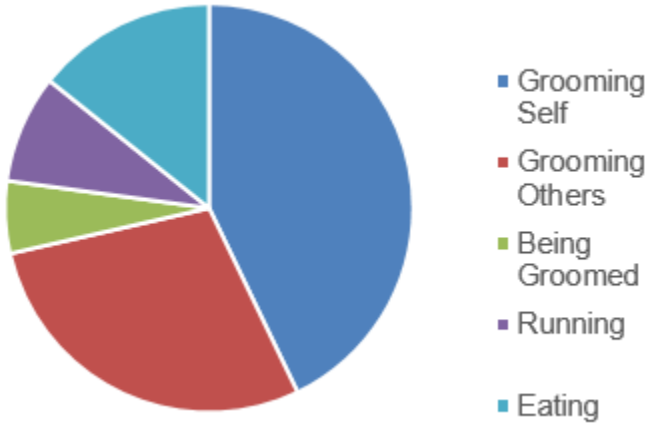



Figure 31. Sample activity budget. (If you will be printing in black and white, remember to use different patterns for the different wedges.)

4. Think about things that may have influenced your findings. Did anything occur during your observation periods that may have influenced your findings? Were conditions similar when you observed the different individuals?

5. Consider how representative your samples of behavior are. Do you think all individuals in the species would have similar activity budgets? Would you see differences at different times of day, different seasons, or in different habitats?

6. You might compare your findings with those reported in the literature for this species. Why might your results be different from those of a long-term study on many individuals? How might the behavior of captive individuals differ from wild ones?

# Key Concepts

- Intraspecific competition takes place between conspecifics. It could be in the form of scramble competition or interference competition (including territoriality).
- Mating systems differ between species—and sometimes populations—depending on environmental conditions and the investments of parents.
- The sex that invests less in the offspring themselves is likely to compete to get more mates, while the sex that invests more in the offspring is likely to be more selective in mates. When mates are socially monogamous, neither sex can be very selective or mate with a large number of individuals.
- Most mating systems still include copulations outside the apparent mating pair or group.
- Conspecifics may benefit each other in multiple ways, even while behaving selfishly.
- Kin selection may result in altruism between relatives.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately explain causes and effects of intraspecific competition*
2. *Accurately describe how conspecifics can benefit each other*
3. *Effectively evaluate the influence of various mating systems on individual fitness*
4. *Accurately analyze how relatedness influences unselfish behavior*

1. Imagine that researchers set up enclosures, stocked them with either low or high densities of insects, then recorded survival (Figure 32).

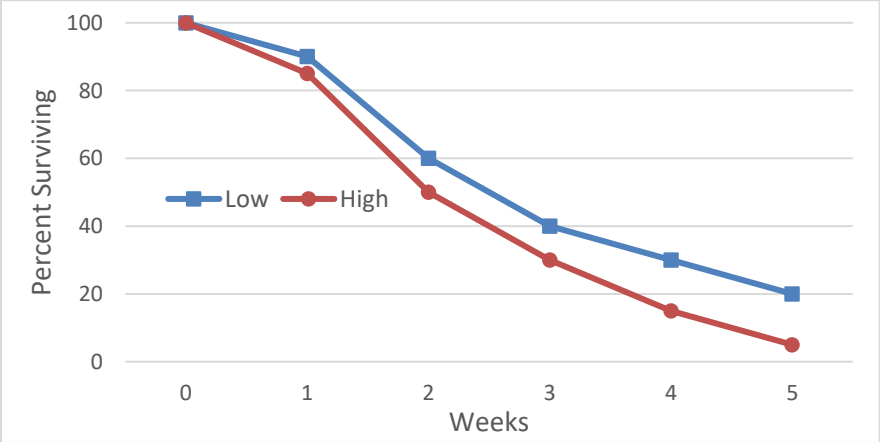



Figure 33. Hypothetical survivorship curve of insects.

A. How did density influence survivorship in the insects? *(Learning Outcome* 1*)*
B. Explain some possible reasons for this pattern. *(Learning Outcome 1)*
C. In another treatment, researchers added a predator. This treatment did not change the survival of the low density insects, but it increased the survival of the high density insects. Explain how this could happen. *(Learning Outcome 1)*

2. Why should male Red-winged blackbirds have territories that are fairly similar in size? Why shouldn't a male try to establish a large territory that might attract 4 or 5 females? *(Learning Outcomes 1 and 3)*

*3.* How does kin selection explain why a mother might risk her life to keep a predator away from her offspring? *(Learning Outcome 4)*

4. Imagine a study on birds that can form pairs but either nest alone or share their nest with other pairs and share duties such as nest building, feeding offspring, and protecting the nest from predators.

   A. Explain how a nest with more adults could result in higher reproductive success per individual. *(Learning Outcome 2)*
   B. How might the behavior of the birds be different if all the females were related to each other? *(Learning Outcomes 1, 2, 3, and 4)*
   C. If adults couldn't recognize their own eggs or young, how might that influence the behavior of the adults? *(Learning Outcomes 1, 2, 3, and 4)*
   D. Would you predict that male and female birds would be similar in size and appearance? Explain your prediction. *(Learning Outcome 3)*

5. How might the level of resources in an area influence mating systems? For example, might polygyny or monogamy be more common in a species of birds if their food were plentiful during the nesting season? *(Learning Outcome 3)*

**Unit IV: Populations**

# Chapter 12: Population Size and How it Changes

**Case Study Part 1: Where Do All the Lemmings Go?**

Many people believe that lemmings (Figure 1) jump off cliffs and drown when their populations get too big. Natural selection would obviously not favor this trait. The lemmings that did not have the gene for suicide would be the parents of the next generation and such a gene would be quickly lost from the population.

https://commons.wikimedia.org/wiki/File:Lemmings_at_Amsterdam_Zoo_-_Artis_%2826252016066%29.jpg

Figure 1. Lemmings (*Ctenodactylus gundi*) have extreme population cycles that have led to the myth that the are suicidal.

The basis for the myth is that several species of lemmings do have wide swings in their population size. For several years, they may be very rare. Then they suddenly seem to over-run the landscape. Soon after, they seem to disappear again. Ecologists have tested many hypotheses about the rapid growth and decline of lemming populations. They have studied weather patterns, the plants that lemmings eat, the predators of lemmings, other small rodents that may eat the same food or have the same predators, and a variety of other factors. In this chapter, you will learn about factors that can influence population size. Then you will find out how these factors might explain the dramatic population cycles of the lemmings.

**Learning from the Case Study**

- Why is it unreasonable to think that lemmings would commit mass suicide?
- What could cause occasional, large increases in population size?
- What could cause a large population to suddenly crash, leaving few individuals?

# Learning Outcomes

1. *Accurately interpret models of changes in population size*
2. *Make and defend valid predictions of future population size*
3. *Propose reasonable explanations of patterns in population size*

**Vocabulary Toolkit**

**Word Watch List**

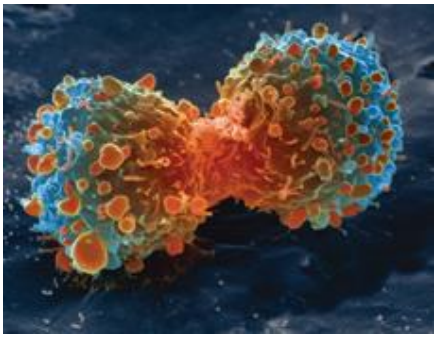
**Geometric growth**: Population growth when there are discrete breeding seasons or generations do not overlap (e.g. annual plants that die before their seeds sprout)
**Exponential growth**: Population growth when generations overlap and reproduction is continuous
**Population density**: Number of individuals per unit area or volume
**Density-dependent factors**: Variables that tend to limit populations more as population size increases (e.g. resources become scarce when populations are high)
**Density-independent factors**: Variables that limit population size, but are not influenced by population size (e.g. floods are not more common when populations are high)
**Carrying capacity**: The number of individuals that an area can sustainably support
**Logistic growth**: Population growth that starts as exponential, then slows as it approaches carrying capacity. It levels off when it reaches carrying capacity
**Age distribution**: Pattern of young and old individuals in a population
**Sex ratio**: Proportion of males to females in a population

## Populations Change

Recall from Chapter 11 that a biological population includes all the members of one species in a particular place. It could be the number of wolves in Yellowstone National Park, the number of crows in your county, or the number of bacteria of the same species in your tuna sandwich. Understanding patterns of population growth and why they happen helps people manage species, protecting valuable populations and controlling harmful invasive species. Governments and businesses model human population size to predict demand for goods and services.

All living things reproduce. As discussed in Chapter 4, they may produce seeds or spores, divide, lay eggs, give birth, or send parts of themselves off to make new individuals (Figure 2). Asexual reproduction produces clones that are genetically identical to the parent and each other. In sexual reproduction, individuals exchange genetic information. Why should organisms swap DNA? Why make an egg that only has half your DNA instead of one that has all of it? Why make sperm that may never find an egg? Recall from chapter 4 that genetic exchange is valuable because it creates genetic variation in offspring. If the world never changed, asexual reproduction would make sense. In reality the environment of the offspring may be different from the environment of the parent. Some organisms reproduce sexually sometimes, but asexually

other times. They benefit from the efficiency of asexual reproduction and the variation of sexual reproduction.



http://commons.wikimedia.org/wiki/File:Lung_cancer_cell_during_cell_division-NIH.jpg

Lung cancer cell dividing mitotically into two genetically identical daughter cells.

https://commons.wikimedia.org/wiki/File:Aspen_trees_2.jpg

Most aspen trees are clones that grow from special structures on roots.

http://en.wikipedia.org/wiki/Puffball

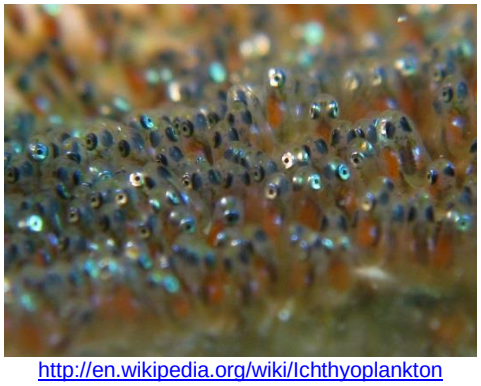
Puffball shedding a cloud of fungal spores that were produced asexually.

http://en.wikipedia.org/wiki/Budding

*Hydra* budding off two smaller, genetically identical individuals, one on either side.

https://commons.wikimedia.org/wiki/File:Sunflower_with_black_seeds.png

Sunflower seeds. Each seed is genetically different from the other and the parents.



http://en.wikipedia.org/wiki/Ichthyoplankton

Anemone fish eggs. Each fish is genetically different from the other and the parents.

Figure 2. Various forms of asexual and sexual reproduction.

**Misconception Alert: Plants reproduce asexually and animals reproduce sexually**

**FALSE.** Sexual reproduction simply means that genetic information (DNA) is exchanged between individuals. Plants often reproduce asexually, sending out parts of themselves that sprout new individuals. You may have taken a cutting from a friend's plant and grown it yourself. That is asexual reproduction. Plants also reproduce sexually when pollen from one plant fertilizes eggs on another plant. Although asexual reproduction is rare in vertebrates, many invertebrates can reproduce by budding off parts of themselves. Some species of plants and animals alternate sexual and asexual reproduction.

As you drive into a city, you are usually greeted by a sign telling you the population size. Maybe it says 3,121,912. Maybe it says 372. Is it likely that these numbers are accurate? If the sign is new, it is probably fairly close, but population sizes are constantly changing. What changes the population size? Individuals are being born and dying. They are moving away and moving in. Unless the number of individuals entering the population exactly matches the number leaving it, population size will change. Roughly the same thing could be said of any population. Individuals may sprout, hatch, or be the result of cell division, but the idea is the same.

Ecologists use models to describe and predict changes in population size. Population size increases with each birth and decreases with each death. Another way to write this concept is with an equation. (**Model Skill: Working with Equations** provides advice on solving problems with equations.)

N = The number of individuals in a population
B = The number of births
D = The number of deaths

Each of these letters is a variable. Together, they allow us to estimate changes in the population size. We will assume that movement in to the area balances movement out. Usually, we know the number of individuals in a population now, and we want to know the number at a particular time in the future. We can use a subscript to show which time we mean. For example:

$N_{now}$ = The number of individuals in a population now
$N_{next\ year}$ = The number of individuals in a population next year.

So we can write an equation for predicting population size:

$$N_{next\ year} = N_{now} + B - D$$

A more efficient way to do this is to use a shorter label. We can use write the number in the population as $N_t$, where t = amount of time.

$N_{one\ year\ from\ now} = N_1$
$N_{now} = N_0$ because it's zero years from now.

Now we can write an efficient equation for predicting population size:

$N_1 = N_0 + B - D$

Let's say that a city has 100,000 people this year. If 1400 are born, and 1000 die, what will the population be next year?

$N_1 = N_0 + B - D$

And

$N_0 = N_{now} = 100{,}000$
t = One year from now = 1
B = The number of births = 1400
D = The number of deaths = 1000

So $N_1 = 100{,}000 + 1400 - 1000$

Next year there will be 100,400 people in the city.

**Model Skill: Working with Equations**

Equations express relationships between variables. These relationships can be complicated, but equations represent them efficiently. When you first see equations, translate them into words. As you calculate changes in population size, notice that using sentences instead of equations to describe relationships would be much more time-consuming.

When you use an equation, first write out the general equation, such as:

$N_1 = N_0 + B - D$

Then the values of all the variables, for example:

$N_0 = N_{now} = 100{,}400$
t = One year from now = 1
B = The number of births = 1,200
D = The number of deaths = 1,100

Next, write out the equation, filling in the values you know:
$N_1 = 100{,}400 + 1{,}200 – 1{,}100$

Then write the solution.
$N_1 = 100{,}500$

If the solution takes multiple steps, use a new line for each step. Shortcuts cause errors. Keep things neat so that you do not confuse yourself.

**Check Your Understanding**

- Name two factors that can increase population size.
- Name two factors that can decrease population size.

- Why would we expect populations to change often?
- Why is it important to predict the size populations in the future?
- Why might accurate predictions be difficult to make?

**Populations Can Grow Geometrically or Exponentially**

When population size is increasing, it can grow very fast. The new members of the population can reproduce, so the rate of growth can increase. Imagine a population of deer (Figure 3) that starts off with 100. If each female has one fawn (offspring), we can predict what will happen to the population size.

http://www.dfw.state.or.us/news/images/2014/050614_doe_fawns.jpg

Figure 3. White-tailed deer (*Odocoileus virginianus*) mother and fawns.

$N_1 = N_0 + B - D$

We know that $N_0 = 100$

Births = the number of deer X the number born per deer

The number born per deer can be calculated using a previous year's data by dividing the total number of deer born by the total population size. It can also be determined by using average birth rates per female. If each female has one fawn on average, and half of the deer are female, then an average of ½ a fawn is born per deer. (One is born for every two deer because the males are not giving birth.)

$B = N_0 \times 0.5$
$= 100 \times 0.5$
$= 50$

Let's say that a quarter of the population is dying every year

$D = N_0 \times 0.25$

= 100 X 0.25
= 25

We can predict what will happen to the population size.

$N_1 = N_0 + B - D$

$N_1 = 100 + 50 – 25 = 125.$

So after the first year, there would be 125 total deer. Calculate the numbers for year 2. Your value for $N_0$ will now be 125 deer. Round off the numbers to the nearest whole deer. Add your values to Table 1.

Table 1. Population growth in a hypothetical deer population, rounded to the nearest deer. Note that the ending number of one year is the starting number of the next year. Add the values you calculated.

| Year | Number of Deer at Start ($N_0$) | Number Born ($N_0$ X 0.5) | Number Dying ($N_0$ X 0.25) | Number of Deer at End ($N_1 = N_0 + B – D$) |
|---|---|---|---|---|
| Start | **100** | 50 | 25 | 125 |
| 1 | **125** | | | |
| 2 | | 78 | 39 | 195 |
| 3 | **195** | 98 | 49 | 244 |
| 4 | **244** | 122 | 61 | 305 |
| 5 | **305** | 153 | 76 | 381 |
| 6 | **381** | 191 | 95 | 477 |
| 7 | **477** | 238 | 119 | 596 |
| 8 | **596** | 298 | 149 | 745 |
| 9 | **745** | 373 | 186 | 931 |
| 10 | **931** | 466 | 233 | 1164 |

If individuals entering or leaving the area are an important factor, they would be included as well. Immigrants (I; individuals that enter the population from another area) would be added to the population. Emigrants (E; individuals that leave the population for another area) would be subtracted:

$N_1 = N_0 + B + I – D – E$

Scientists usually look at population numbers as visual models, such as graphs. Deer numbers rise rapidly in the hypothetical population (Figure 4).

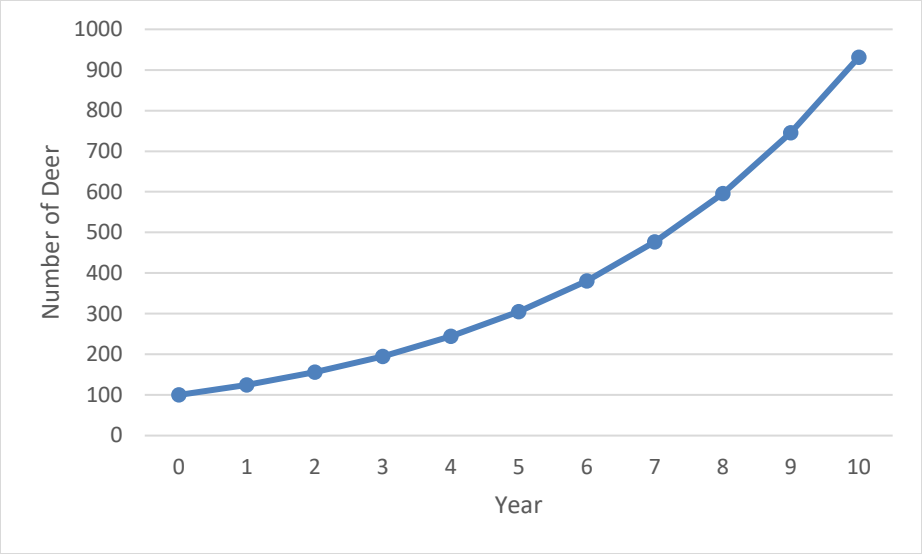



Figure 4. Size of a hypothetical deer population. It started with a population of 100. Each year, 1.25 deer are added for every existing deer.

**Analyze the Figure**

- Approximately how long did it take the population to double from 100 to 200?
- Predict how long it will take the population to double from 600 to 1200.
- Approximately how many deer were in the population by year 10?

Notice that the rise in Figure 4 is not a straight line. The numbers are not just going up; they are going up faster and faster as more and more individuals reproduce at a constant rate. The model we used is for **geometric growth**. After 20 years, there would be almost 11,000 deer. The geometric equation assumes that individuals are not reproducing continuously. This is true for species that breed once per year (or other interval) or annual plants, which grow from seed to adult in less than a year, produce seeds, and die. The **exponential growth** model assumes that individuals can reproduce throughout the time interval. It predicts slightly higher population levels because adults potentially reproduce while some of their offspring are reproducing (Figure 5; see **Taking It Further: The Geometric and Exponential Growth Equations** for details of the model). To try this with an actual population, see **Do Try this at Home: Exponential Growth**.

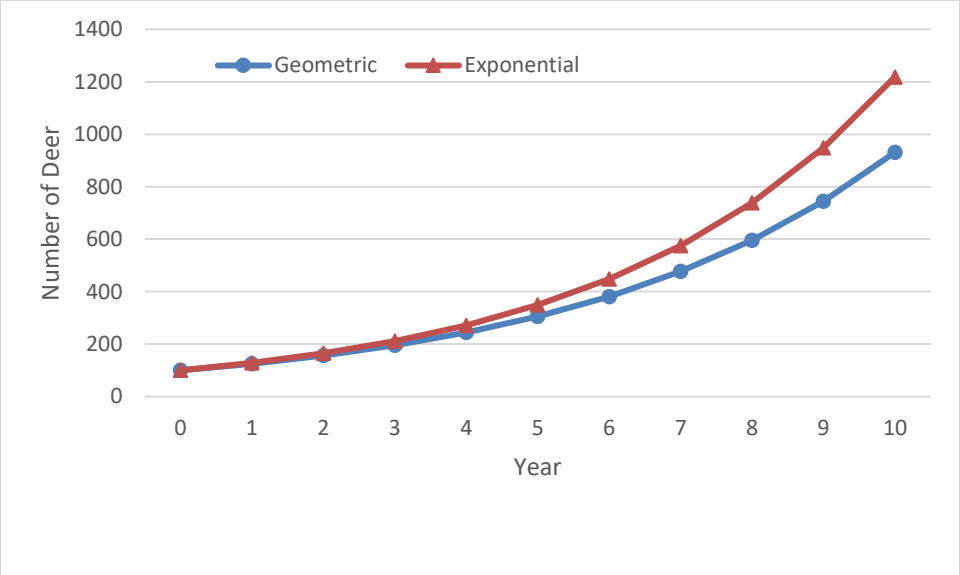



Figure 5. Exponential growth and geometric growth in a hypothetical population of deer with a starting value of 100 and a per deer reproductive rate of 0.25.

**Analyze the Figure**

- Approximately how long did it take the population to double from 100 to 200 using the exponential model?
- Approximately how long did it take the population to double from 600 to 1200 using the exponential model?
- Approximately how many deer were in the population by year 10 in the exponential model?
- In the last year, was population growth higher in the geometric model or the exponential model?

**Taking It Further: The Geometric and Exponential Growth Equations**

The year-by-year method used to calculate the growth in a deer herd would be time-consuming. Using an equation that allows predictions over any time period is more efficient. We will use some of the same variables and a new one, the Greek letter lambda $\lambda$ in the **geometric growth equation**:

$$N_t = N_0 \lambda^t$$

Where:

t = Number of time intervals (we'll use years)
$N_t$ = Number of individuals t years from now
$N_0$ = Number of individuals now
$\lambda = N_1/N_0$ = Number of total individuals next year for every individual this year. In our deer example, that is 125/100 = 1.25.

We can use this equation to predict the deer population size for year 10.

$$N_{10} = N_0 \lambda^{10}$$

So: $N_{10} = 100 \times 1.25^{10}$

To check your work, look at the number for the start of year 10 in Table 1.

Another model used to analyze and predict population growth is the **exponential growth model**. It assumes that reproduction is more or less continuous, instead of in regular intervals, such as one breeding season a year. We will be using two new terms in this equation:

$$N_t = N_0 e^{r\,t}$$

Where:

t = Number of time intervals (we'll use years for the deer)
$N_t$ = Number of individuals t years from now
$N_0$ = Number of individuals now
r = rate of increase per individual.
*e* = a constant with a value of about 2.718. It is the inverse of the natural log.

In the deer example, we assumed that r = 0.25. To predict the population size 10 years after starting with 100 deer, the values would be:

t = 10
$N_t$ = Number of individuals t years from now
$N_0$ = 100
r = 0.25

The equation would be:

$N_{10} = 100e^{(0.25)(10)}$ or $N_{10} = 100e^{2.5}$

This is about 1,218, which is higher than the geometric model predicted. The difference between these models increases with time (Figure 5).

**Do Try this at Home: Exponential Growth**

What you will need:

- Yeast (from the baking aisle of the grocery store)
- Teaspoon of sugar.
- A plastic plate and cup
- Warm water
- Waterproof marker
- Sheet of clear plastic

The grains of yeast we use to make bread, beer, and wine are actually clusters of microscopic fungi. Their populations can grow very rapidly.

Hold a dinner plate under warm running water. Place it on a flat surface. Fill a small cup with water that is warm, but not hot. Mix in about a teaspoon of sugar. Pour a thin layer of this on the plate. Now add a tiny amount of yeast to the center. Check on your yeast several times over the next 30 minutes.

To quantify the changes in population size, use a disposable plastic plate and draw grid lines on it with a waterproof marker. Then estimate the area covered by the yeast by describing portions of the grid that are filled with yeast. You could instead draw the grid lines on a sheet of clear plastic and place this over the plate. Record the time in minutes.

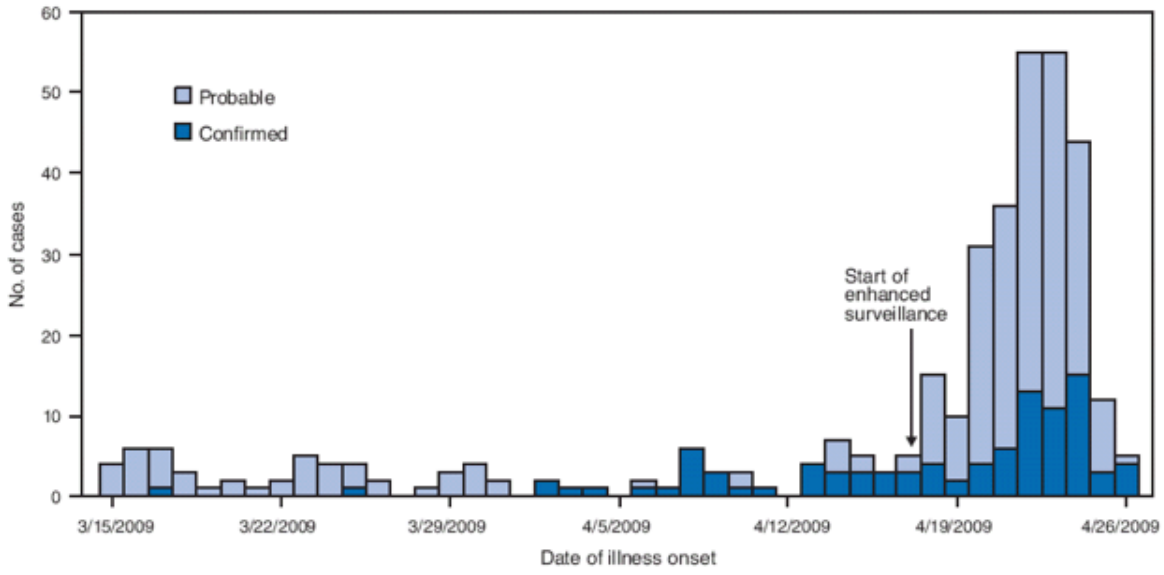
What do you predict would happen if you did not add sugar?

Do actual populations follow the pattern the model predicts? Models are always neater than actual data. All models are based on assumptions. The population model we used assumes that the difference between birth and death rates remains constant. Is this a reasonable assumption? In some years, resources may be high. In other years, scarce food, predators, or diseases may decrease the birth rate and increase the death rate. Exponential growth can used to model the number of people infected with a disease. See **Make the Medical Connection: Exponential Growth and Infectious Disease**.

**Make the Medical Connection: Exponential Growth and Infectious Disease**

Infectious disease epidemics often follow exponential growth curves. Each infected person may spread the disease to many others, who then continue the spread. In densely-populated cities, the risk is very high.

In March of 2009, cases of severe respiratory flu started to appear in Mexico. At first, health officials did not know the identity of the disease, but they reported it and submitted samples for genetic analysis. The disease was identified as Influenza A (H1N1), commonly called "swine flu." Government health offices alerted hospitals to watch for the disease and report any suspected cases. In early April, the number of confirmed cases began to rise exponentially (Figure 10).




https://www.cdc.gov/mmwr/preview/mmwrhtml/mm58d0430a2.htm

Figure 10. Confirmed and probable cases of Influenza A H1N1 in Mexico during March and April of 2009.

Several measures stopped the spread of the disease. The president of Mexico closed all schools in Mexico City on April 24 and closed every school in Mexico three days later. Travelers were informed of the dangers of the disease and how to seek treatment. The government sponsored a national campaign teaching people to avoid spreading the illness, distributed masks and hand sanitizer, and discouraged any large gatherings. People with the disease could be quarantined in their homes. At least 84 people died in the epidemic, but public health efforts may have prevented a higher death toll.

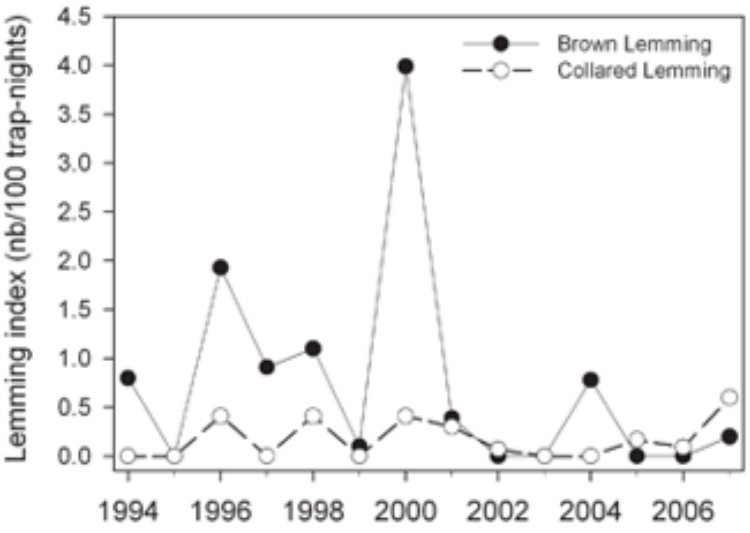
**Case Study Part 2: Where Do All the Lemmings Come From?**

There are several species of lemmings in various tundra regions where winter can last nine or ten months a year. Bylot Island, located in the north of Canada has brown lemmings and collared lemmings (Figure 8). Researchers have tracked their populations by trapping the rodents during the spring and summer. Figure 9 shows how numbers of these two species of lemmings have changed over the years from 1994 to 2007

http://www.arcticphoto.co.uk/supergal/wl/wl01/wl0104-00.htm

http://www.helsinki.fi/science/metapop/species/lemmings.html

Figure 8. Brown lemming (*Lemmus trimucronatus*, left) and collared lemming (*Dicrostonyx groenlandicus*, right). Both are small rodents.




Modified from: http://www.cen.ulaval.ca/bylot/ecomon-anispec-lemmings.htm

Figure 9. Brown and collared lemming populations from Bylot Island, as measured by trapping success. nb = number trapped. Trap nights are calculated by multiplying the number of traps used by the number of nights they were set.

**Analyze the Figure**

- What was the approximate number of brown lemmings captured per trap night in 1999?

- What was the approximate number of brown lemmings captured per trap night in 2000?
- Did the two species have high populations at the same time?

Lemmings spend the winter months below the snow in burrows that they insulate with dried plants. They stay active all winter, eating the plants beneath the snow. They even breed during the winter, which is unusual for rodents. Pregnancy lasts less than a month. The female can mate again right after she gives birth. When females are 2-4 months old, they can breed. Collared lemmings have two or three litters a year of up to eight young. Brown lemmings can have up to nine young per litter and can breed three times a year. (For more on calculating reproductive rate under optimal conditions, see **Taking It Further: Calculating Maximum Reproductive Output per Individual**.)

Imagine starting with two lemmings, one male and one female. If the female has 2 litters of 8 over the winter, there would be 18 lemmings (the original pair plus 16 young). That would be a lot of lemmings appearing when the snow melted. What if some of the females born over the winter had their own litters before spring? Numbers could be huge. That is the power of exponential growth, which occurs when the females are still breeding while their offspring are breeding. Lemmings under the snow are generally safe from predators. All of these lemmings appearing at once in spring would be a dramatic event.

A study on a lemming species in Northern Europe (*Lemmus lemmus*) supports the hypothesis that exponential growth due to winter breeding explains the large, rapid increases in lemming populations. Other small rodents that live in the same environment, but do not breed in winter, do not have such extreme increases in number. Lemmings at higher altitudes, with longer winters, have higher maximum population growth than lemmings that live at low altitude. A thicker snow layer may provide more insulation, keeping lemming burrows warmer. It can also make arctic foxes less likely to prey on lemmings. One study used fencing to create a deeper snow layer over lemming burrows and showed that deeper snow led to higher lemming survival and reproduction.

Other factors could also cause the cycles. There is evidence that dramatic increases in lemming numbers also tend to happen when other rodent numbers are high and predators are specializing on a non-lemming diet. Changes in vegetation could also be a part of the story. For a discussion of why populations might suddenly drop, see **Case Study, Part 3**.

**Learning from the Case Study**

- Why do lemming populations grow so rapidly?
- Why might some years have higher populations than others?
- What might happen to lemming population cycles if deep snow became more or less common with climate change?

**Taking It Further: Calculating Maximum Reproductive Output per Individual**

The per capita rate of increase (r) is the number of new individuals produced per individual in a population. It varies with environmental conditions, including population size (N). If resources are low, or pathogen levels are high, r could be low, zero, or negative. The lowest possible value for r is -1, meaning that every individual in the current population would be dead by the next time interval.

The maximum possible per capita rate of increase for a particular species is its **intrinsic rate of increase** ($r_{max}$). This rate assumes the best possible circumstances. In reality $r_{max}$ will probably never be achieved by any population, but it can be helpful to know the maximum and minimum values of any variable.

To calculate $r_{max}$, determine the *maximum* number of offspring that can be produced per individual under optimal conditions and subtract the *minimum* number that would die per individual under optimal conditions.

1. Select an appropriate time interval. For vertebrates and many plants, it will probably be a year, but some species reproduce much faster. Use this interval consistently.
2. Find the maximum number off offspring produced at a time (litter size, clutch size, seed output, or other measure).
3. Multiply this by the maximum number of times an individual produces offspring during a time interval
4. If there are separate sexes, and the proportion of males and females in the population are roughly equal, divide they number of offspring per female by two (because there is one female for every two individuals).
5. If only a fraction of the individuals in the population are producing offspring, multiply the output per reproductive individual by this fraction (for example, if 1/3 of the population is too young to reproduce, divide the per/individual output by 2/3).
6. Subtract the per capita death rate. It is useful to assume that the population is evenly divided between age groups, even though this is rarely true. If the maximum life expectancy is one year, then all (1/1) will die in one year. If the maximum life expectancy is two years, then half (1/2) will die in one year. The minimum per capita death rate is 1/maximum lifespan.

Other factors may be important in calculating $r_{max}$, depending on the species.

**Check Your Understanding**

- What is the difference in assumptions between exponential and geometric growth models?
- How does the *rate* of population growth change in either the exponential or geometric growth models?
- Do either the exponential or geometric growth models include a limit on population size?

## Growth has Limits

What prevents actual populations from expanding exponentially forever? Every species has specific needs, which may include food or sunlight, nutrients, water, space, or even other species as hosts. Resources such as these can limit populations. **Population density** is the number of individuals in a particular space. As the density of the population increases, resources are used, pathogens spread more easily, predators may be attracted or breed more. In some habitats, wastes may build up when populations are large. Because these factors get worse as population density increases, they are called **density-dependent** factors.

Other factors that can reduce population size are not influenced by the density of the population. These include major storms, volcanic eruptions, and other events that happen regardless of the population size. These are called **density-independent** factors. Not everything fits neatly into either of these categories. Prairie fires may be more common when the density of grass increases, but not when the density of prairie rattlesnakes increases. A disaster for one species may benefit another or have little effect on yet another.

The total number of individuals of a species that an area can support is called the **carrying capacity** of that area, abbreviated as K. Carrying capacity varies in time and space due to conditions. For example, one reserve can support 100 deer per square km. A place that is colder or drier would have a much lower carrying capacity. A place with milder winters and more food could have a higher carrying capacity. Would the carrying capacity be the same all the time? No. A long drought, a disease that killed the deer's food, or even over-eating by the deer themselves could lead to a lower carrying capacity.

We usually only see long periods of exponential growth when populations are recovering from major die-offs or when they invade a new area. As population size approaches carrying capacity, density-dependent factors usually cause decreases in the birth rate and increases in the death rate. Individuals may be starved for resources, ill, damaged from fighting, or poisoned by environmental toxins. Crowding itself can cause stress that decreases reproduction and immune system function.

The **logistic growth** model (red line in Figure 11) describes what happens as populations reach carrying capacity. The model starts with exponential growth. As the population size (N) approaches carrying capacity (K), growth (r) slows to zero. Then the population size stays at carrying capacity. **Taking It Further: The Logistic Growth Equation** explains the equation that results in this curve. Actual populations show more variation than the model.

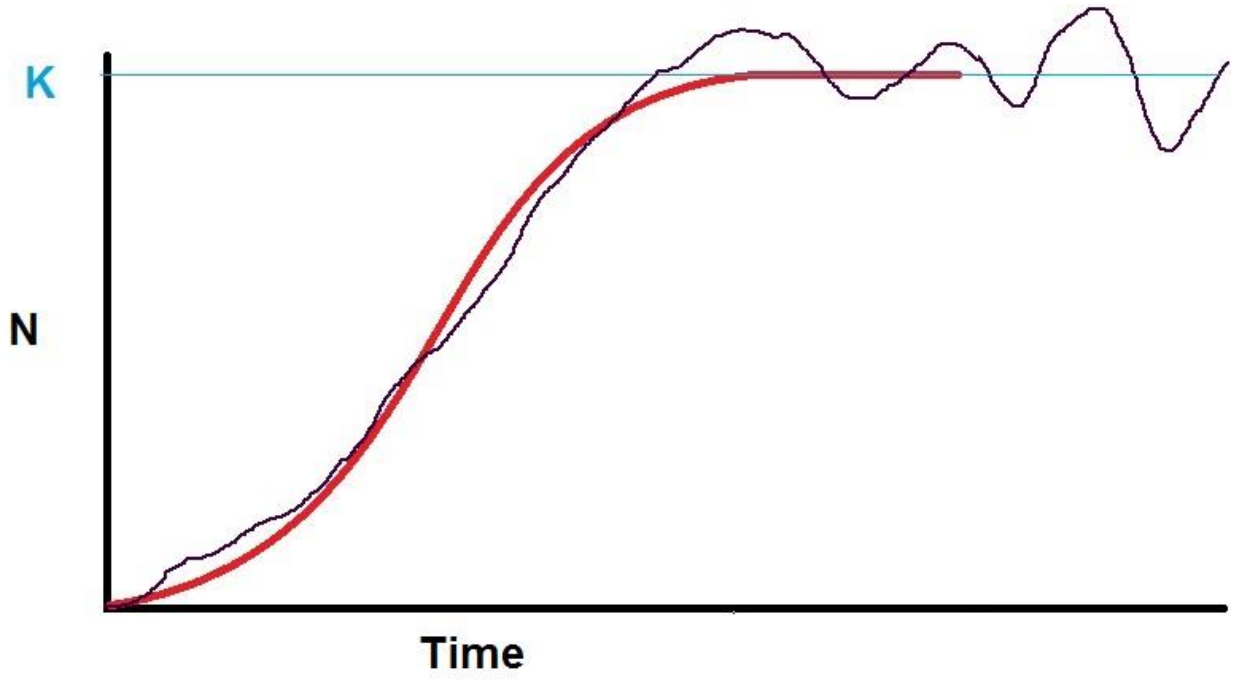



Figure 11. Model (red line) and a hypothetical example (purple line) of population size (N). Carrying capacity (K; light blue line) limits population growth.

**Analyze the Figure**

- What happens to the *rate* of increase in population size (N) as the population approaches the carrying capacity (K)?
- Does the actual population stay at the carrying capacity?
- Why might an actual population not be the same as the model?

In a model, the transition from growth to a stable number is smooth. Actual populations may also start to level off or even decline at some point as density-dependent factors start to reduce reproduction and increase death. Because populations have no way to "look ahead" and manage their own populations, they often overshoot the carrying capacity. The population gets bigger than the environment can support, then there is a die-off, usually due to density-dependent factors such as starvation and disease. After the die-off, more resources are available, so numbers tend to increase. In the long term, actual populations tend to vary above or below the carrying capacity. Some species overshoot the carrying capacity dramatically and often. Other species have fairly stable populations near carrying capacity. This will be discussed more in Chapter 13. For more on density-dependent and density-independent control in populations, see **Hypothesis Testing: What Controls Populations of Malaria Vectors?**

**Taking It Further: The Logistic Growth Equation**

The logistic growth equation is a model of what happens as population size approaches carrying capacity. The differential equation can be approximated as:

$$B = r_{max} N (1- \frac{N}{K})$$

Where:

B = Number born in a population in a time interval
$r_{max}$ = Intrinsic rate of increase; maximum births per individual (see **Taking It Further: Calculating Maximum Reproductive Output per Individual**)
N = Number of individuals in population.
K = Carrying capacity; total number of individual environment can support.

For example, assume that:

- $r_{max}$ for snow leopards = 2
- A reserve can hold 10 snow leopards
- The population starts with a pair of snow leopards (1 male, 1 female)

In year 1:

$B = (2)(2)(1- \frac{2}{10})$
$= (2)(2)(0.8)$
$= 3.2$

Rounded to the nearest cub, 3 were born. There were already 2. So the value for N in year 2 would be 5.

In year 2:

$B = (2)(5)(1- \frac{5}{10})$
$= (2)(5)(0.5)$
$= 5$

There were 5 snow leopards at the start of year 2, so year 3 would start with 10.

In year 3:

$B = (2)(10)(1- \frac{10}{10})$
$= (2)(10)(0)$
$= 0$

The population size has reached carrying capacity so it is no longer increasing. Because this is a model (not the real world) the value of N will be 10 for all future years rather than overshooting K and crashing or cycling around K. Why do you think the model uses $r_{max}$ instead of r?

Having a reasonable estimate of carrying capacity allows people in natural resource management to set realistic goals for population size and harvest levels that maintain healthy population levels (see **Why It Matters: Carrying Capacity and Harvest**).

### Hypothesis Testing: What Controls Populations of Malaria Vectors?

Researchers in Tanzania applied the concepts of population dynamics to understand a critical public health issue. Hundreds of millions of people in Africa get malaria each year. About 1 million people die from the disease. Protecting people from the mosquitoes that spread malaria (Figure 12) can prevent much suffering and death.

https://commons.wikimedia.org/wiki/
File:Anopheles_gambiae_mosquito_feeding_1354.p_lores.jpg

Figure 12. Female mosquito (*Anopheles gambiae*) taking blood from a human. As they feed, the mosquitoes can spread the parasite that causes malaria.

Researchers interested in mosquito control tested three hypotheses regarding how population size in this species of mosquito is controlled:

- Populations are controlled only by density-independent factors
- Populations are controlled only by density-dependent factors
- Populations are controlled by both density-independent and density-dependent factors.

If only density-independent factors control the mosquito populations, then controls such as poisoning might be very effective at reducing population size. The remaining mosquitoes would not be able to increase their reproductive output when populations were low.

If only density-dependent factors are important in controlling mosquito population size, it would mean that a few survivors could increase their reproduction to take advantage of the increase in their resources. Control efforts would be less effective than expected because the mosquito population would increase faster at low populations than at high populations.

Over 84,000 female mosquitoes were collected using traps set near people sleeping under protective mosquito nets. (Only female mosquitoes take blood.) Researchers counted the mosquitoes and used genetic analysis to identify the species of interest for the study. They calculated how many new mosquitoes were being produced per mosquito in the population (the per capita growth rate of the population, r). They then tested whether the mosquitoes were reproducing more when their population was low (Figure 13 A). Measurement data showed that mosquitoes were smaller when their density was high.

The research team wondered whether variation in a density-independent variable might be hiding a relationship between population size and reproductive rate. Mosquitoes lay their eggs in water. Larvae mature in the water for about two weeks. The amount of rainfall would influence the number of pools available, and therefore the carrying capacity (K) of the area for mosquitoes. So another model was created that accounted for differences in rainfall (Figure 13 B).

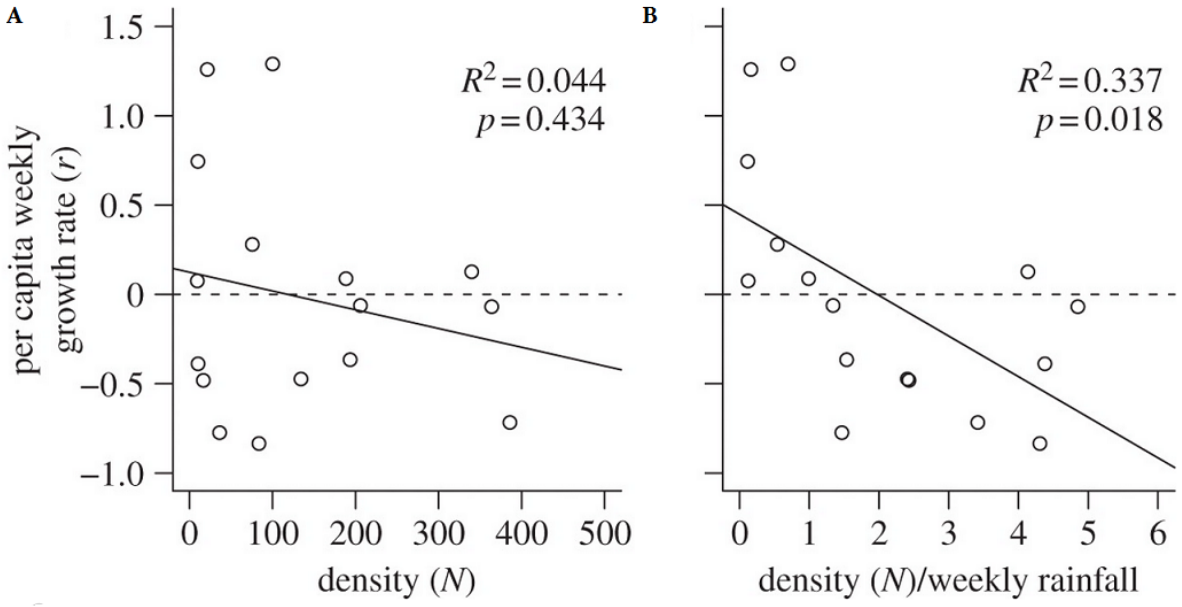



Figure 13. **A**. Influence of mosquito density (a measure of N) on per capita growth rate (r). (See Appendix C to review the meaning of $r^2$ and p-values). **B**. Influence of mosquito density and weekly rainfall on per capita growth rate. The dashed line indicates no change in population size. Negative numbers indicate a population decline. Modified from: Russell, T. L., Lwetoijera, D. W., Knols, B. G., Takken, W., Killeen, G. F., & Ferguson, H. M. (2011). Linking individual phenotype to density-dependent population growth: the influence of body size on the population dynamics of malaria vectors. *Proceedings of the Royal Society of London B: Biological Sciences*, rspb20110153.

**Analyze the Figure**

- Does density alone determine the per capita weekly growth rate?
- Does the inclusion of rainfall make the model a useful predictor of weekly growth rate?
- Which of the hypotheses are supported by these graphs?

Mosquitoes could reproduce more when their numbers were low. This was bad news, but including this information made the predictions about mosquito population size more accurate. The results also suggested that targeting the larvae would be the best way to control population numbers. The more larvae are crowded in pools, the smaller the larvae are and the less they reproduce when they mature. Using insecticides on adults would just allow the remaining adults to increase their reproductive output. Larvae that were less crowded in pools would grow up to produce more offspring. On the other hand, helping people eliminate pools of water near their homes would reduce carrying capacity. Using insecticide on the remaining pools would kill the larvae before they reproduce.

**Why It Matters: Carrying Capacity and Harvest**

We get food, materials, medicine, and many other resources from wild species. If there is no regulation of harvest, populations may be over-exploited to extinction (see Tragedy of the Commons in Chapter 2). If harvest limits are too low, populations may overshoot their carrying capacity, degrade their environment, and crash. It might seem obvious to set regulations so that populations stay just below carrying capacity. A high limit allows for the largest harvest. But carrying capacity varies at different times and in different places. People can only estimate the carrying capacity based on what they have observed in the past.

Anchovies are small fish that are used for food. There is no way for anyone to know the exact number of anchovies in the ocean. The history of anchovy catch is the best number available for setting a catch limit. The anchovy catch for waters around Peru have varied a lot from 1950 to 2000 (Figure 14).

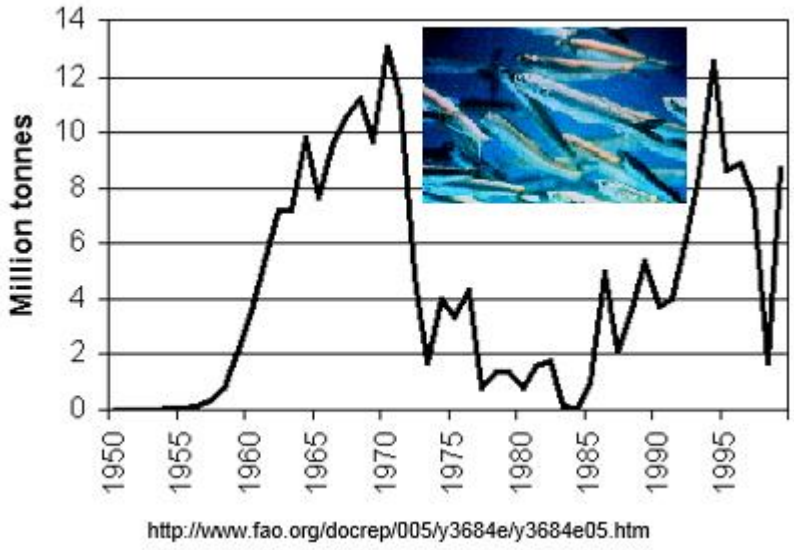



Figure 14. Annual catch of anchovies in Peruvian waters. Source of photo: https://en.wikipedia.org/wiki/Anchovy#/media/File:Anchovy_closeup.jpg

- What do you think is a reasonable estimate of carrying capacity of Peruvian waters for anchovies? Support your estimate with data.
- Evaluate the data. Is annual catch the same thing as population size? What might influence the population size? What might influence the catch size?
- Who would be affected by setting the catch limit too high or too low? Are the long-term risks different from the short-term risks? Are they shared by the same people?
- The areas where fish are found may be in international waters. How might this complicate the regulation and management of fisheries?

**Case Study Part 3: What limits the lemmings?**

What might cause lemming populations to crash? Causes could include disease, starvation, or predation. The main predators of lemmings on Bylot Island are Snowy owls, arctic foxes, and ermine (Figure 15).

**A**

http://en.wikipedia.org/wiki/Snowy_owl#/media/
File:Snowy_Owl_-_Schnee-Eule.jpg

**B**

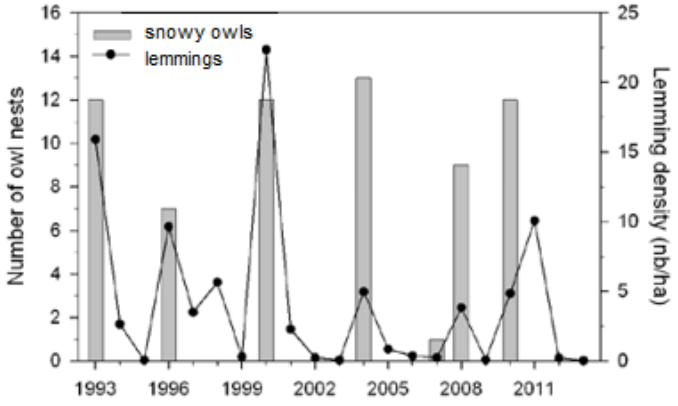
http://en.wikipedia.org/wiki/Arctic_fox#/media/
File:Polarfuchs_1_2004-11-17.jpg

**C**

http://en.wikipedia.org/wiki/Stoat#/media/
File:Mustela_erminea_upright.jpg

Figure 15. Snowy owls (**A**, *Bubo scandiacus*), arctic foxes (**B**, *Vulpes lagopus*), and ermine (**C**, *Mustela erminea*) prey on lemmings on Bylot Island.

High lemming numbers could lead to more reproduction by their predators. Then predators would have to kill more lemmings to feed their hungry young. Researchers tracked the reproductive success of Snowy owls and arctic foxes to look for a pattern like this (Figure 16). Predator-prey cycles are explored further in Chapter 14.



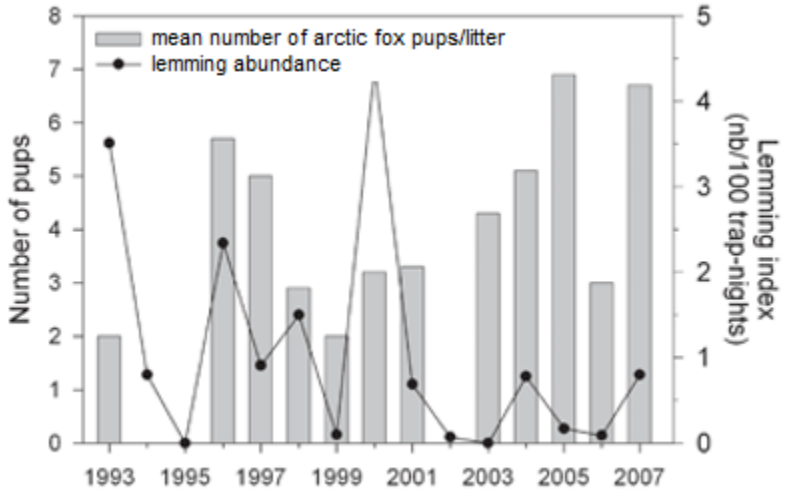

Modified from: http://www.cen.ulaval.ca/bylot/ecomon-anispec-snowyowl.htm

Figure 16. Snowy owl populations (based on number of nests) and lemming populations (based on trapping success) on Bylot Island. Nb/ha = number per hectare—a 100 m by 100 m square. Missing bars for owls mean no Snowy owl nests were found that year.

**Analyze the Figure**

- Do years of high lemming populations also have high owl numbers?
- Do years with no Snowy owl nests match years with low lemming numbers?
- Are there any exceptions to the patterns you identified?
- Will trapping success always be a good indicator of population size?

The data show that Snowy owls tend to have more nests when lemmings are common, but this information does not tell ecologists whether the owls are reducing the lemming numbers. Arctic fox reproductive success was also compared with lemming numbers (Figure 17).




Modified from: http://www.cen.ulaval.ca/bylot/ecomon-anispec-arcticfox.htm

Figure 17. Average number of arctic fox pups produced per litter and lemming populations (based on trapping success) on Bylot Island. Note that the graph has two Y-axes. Missing bars for foxes mean few or no pups were counted that year.

**Analyze the Figure**

- Do years of high lemming populations also have high arctic fox pup numbers?
- Do years with no fox pups match years with low lemming numbers?
- Are there exceptions to the patterns you identified? How would you explain them?

Perhaps numbers of Snowy owls, arctic foxes, or other predators increase with high lemming populations, reducing the lemming populations. Predators can also have a bigger impact on prey if they change their behavior. These predators can eat other prey, such as voles, arctic hares, and snow geese (especially eggs and young). Might predators be switching to a lemming diet when numbers are high? This would mean that the same number of predators would have a higher impact on the lemming numbers. One study showed that arctic foxes specialize on brown lemmings when they are common, but don't specialize on collared lemmings, even when they are common. Another study found that in summer, Snowy owls eat more lemmings than can be produced by reproduction. Snowy owls sometimes surround their nests with the carcasses of

lemmings (https://blog.nature.org/2014/01/21/the-amazing-lemming-the-rodent-behind-the-snowy-owl-invasion/). Starvation, disease, parasites, and natural disasters could all play a role in causing lemming populations to crash. In different years, the causes may be different. We do know that they are not hurling themselves off sea cliffs.

**Learning from the Case Study**

- What factors cause lemming populations to crash?
- If global climate change results in shorter winters, how might that change lemming population cycles?
- How might climate change influence populations of the lemmings' predators?

**Check Your Understanding**

- Distinguish between density-dependent factors and density-independent factors, giving some examples of each.
- Why might carrying capacity vary?
- Can species regulate their population size to avoid reaching carrying capacity?

## Age Distribution and Sex Ratio Can Vary in Populations

Age distribution can show what has happened in the past and allow predictions about the population in the future. Imagine walking through a landscape like the one pictured in Figure 18.

https://commons.wikimedia.org/wiki/File:Savanna-light-shade-2289.jpg

Figure 18. Bur oak trees (*Quercus macrocarpa*) in a Wisconsin savanna.

**Analyze the Figure**

- Do you see any young trees?
- What do you predict will happen as the adult trees die? Will it still be an oak forest?

If you are thinking like an ecologist, you know this population of trees is probably doomed even if all of the trees are healthy. There are no young trees here to replace the old ones when they die. What will happen to a population in the future depends in part on the ages of individuals in the population—the **age distribution**. If conditions prevented reproduction 10 years ago, there will be a lack of 10-year-old individuals in the population. Good years for reproduction will probably result in many individuals of a certain age. As these individuals reach reproductive age, there will probably be an increase in population size. Individuals of different ages will probably have different reproductive outputs and life expectancies.

Ecologists analyze past population patterns and predict future ones using population pyramids. These are specialized bar graphs showing the number or proportion of individuals in each age category. They do not necessarily look like pyramids, as you will see. Consider a hypothetical population pyramid for a species of oak trees in a region (Figure 19).

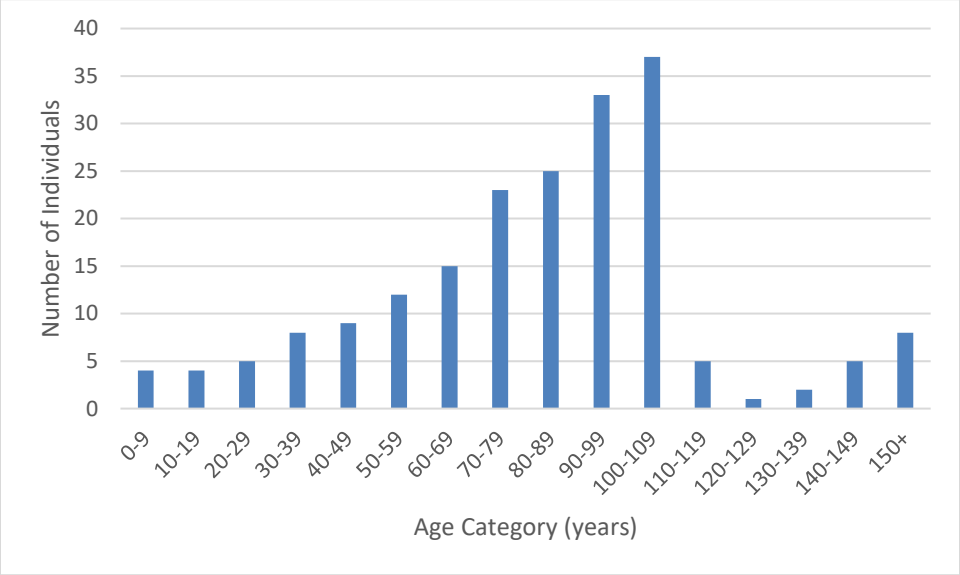


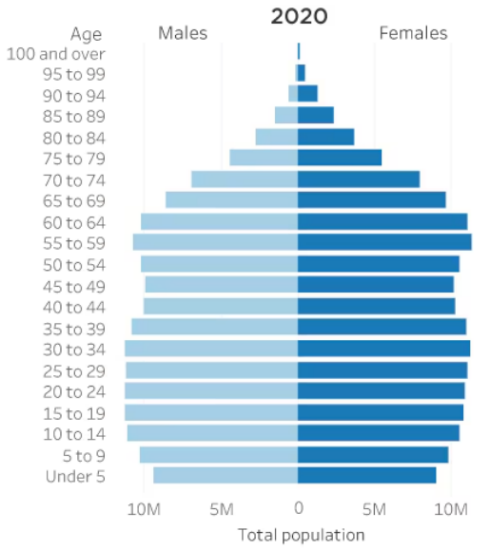
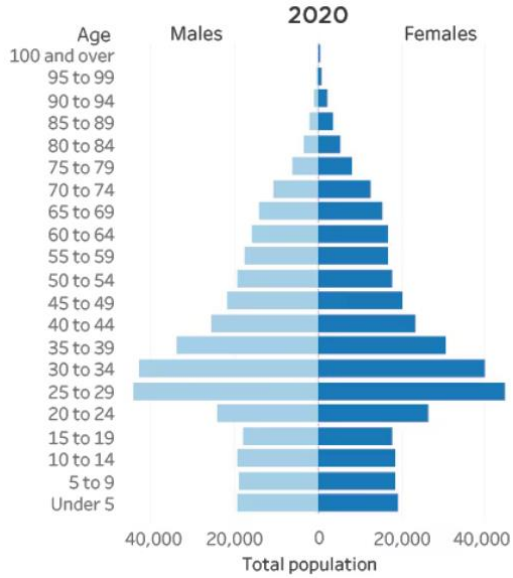

Figure 18. Age pyramid for a population of oak trees.

**Analyze the Figure**

- What may have happened 110-139 years ago?
- What may have happed 100-109 year ago?
- How many trees in the 30-39 age group will there be in 10 years?

Age distribution can be useful in analyzing human populations. Governments, businesses, and non-governmental organizations need reasonable predictions of human population patterns to make good decisions. Will there be a greater need for elementary schools or senior housing? How many people will be retiring in the next twenty years?

Figure 20 contains population pyramids for the United States as a whole and for Denver County, Colorado, USA for 2020. Each bar shows the number of people who belong to a certain age group. Some age pyramids use color to show when women are in the reproductive age category, usually between 15 and 49, though there will be variation. When more women are leaving reproductive age than entering it, population *growth* (r) will start to decline, though the *size* of the population (N) may take a long time to decline.

| United States Population | Denver County, CO, USA Population |
|---|---|
|  |  |



https://www.census.gov/library/stories/2023/05/aging-united-states-population-fewer-children-in-2020.html

Figure 20. Populations of the United States and Denver County, CO, US.

**Analyze the Figure**

- In the US in 2020, about how many people were aged 20-24?
- Compare the populations in the US and Denver County, what patterns do you see?
- How would you explain the differences?

Population pyramids show **sex ratio** is relative number of males and females in a population. Note that in the 2020 US population, there were more women than men in the oldest age categories. In some species, males are not needed for parental care. One male can often fertilize many females (see Chapter 11 for details). Population growth in these species will be influenced more by the number of females than the number of males. For example, there may be only a few male white-tailed deer that have the opportunity to breed. If some male deer are removed from the population, there may be no change in the number of offspring born that year.

In species where only males provide parental care, the opposite may be true. Male sea horses care for the young, so they will limit reproductive population growth. If both parents are needed to successfully raise offspring, an uneven sex ratio in either direction can limit population size because unpaired individuals will not contribute to population growth. The relative costs and benefits of producing males and females may be different under different conditions (See **Evolutionary Perspective: When Sons Aren't Worth the Risk**). Differing costs and benefits of producing each sex can lead to differences in sex ratio in populations.

**Evolutionary Perspective: When Sons Aren't Worth the Risk**

In red deer populations, a dominant male mates with many females (see Chapter 11 for more on mating systems). A small, weak male has little chance of mating. For a female red deer, a son is a high-risk investment. There will be several males with no mating opportunities for every successful male. A daughter is a low-risk investment. She will probably mate every year of her adult life. So which sex should a female produce? Think of this as a game where you could either get a guaranteed $10 or get a 10% chance of getting $100, and a 90% chance of getting nothing. The average payoff is the same, but individual payoffs vary a lot.

Now imagine a year when the population is near carrying capacity. Many females are in poor condition. They are likely to have sons who are small and weak and will have few or no mating opportunities when they grow up. This would be similar to having the risky bet only give you a 1% chance of winning the $100. Now the safe bet—having a daughter—has a higher average payoff than having a son. On the other hand, if a female is in particularly good condition, and likely to have a high ranking son, she might get a big payoff, similar to having a high chance of winning the entire $100. Natural selection should favor females that produce sons if they are in very good shape, but daughters when they are in poor shape. This is the pattern found in one study (Figure 21). When population density was high, there were fewer males born per female. When populations were low, a higher proportion of males was born.

**A**

http://commons.wikimedia.org/wiki/File:Rotwild,_Cervus_elaphus_12.JPG

**B**

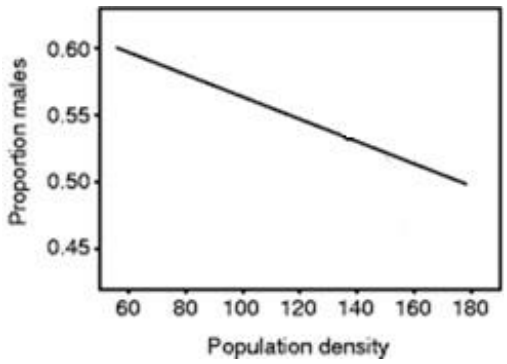



Figure 21. **A**. Red deer (*Cervus elaphus*) mother and fawn. **B**. Proportion of male to female young born in red deer. A proportion of 0.5 would mean an equal number of males and females. Modified from: Kruuk, L. E., Clutton-Brock, T. H., Albon, S. D., Pemberton, J. M., & Guinness, F. E. (1999). Population density affects sex ratio variation in red deer. *Nature*, *399*(6735), 459-461.

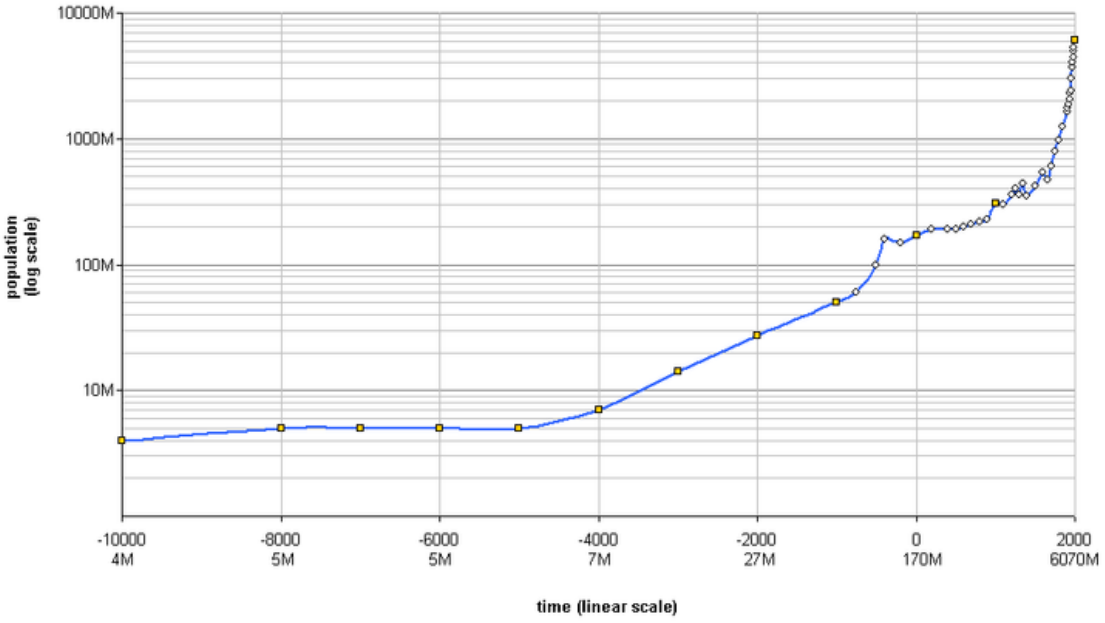
This does not occur because mothers calculate the odds and choose the sex of their offspring. It happens because mothers with genes for producing more males when they are in good condition, and more females when they are in bad condition, leave more copies of their genes in future generations. The mechanism is still unknown.

## Check Your Understanding

- How does the shape of an age pyramid allow ecologist to predict population changes?
- How do higher proportions of females or males influence populations differently?

## Is there a Limit to Human Population?

We can infer the pattern of human population change over the last 10,000 years (Figure 22). Early estimates are from archeological data. Later estimates are based on government records.




http://commons.wikimedia.org/wiki/File:World_population_growth_(lin-log_scale).png

Figure 22. Log of estimated global human population size from 10,000 BCE to 2000 CE. The numbers below the years are estimates of the population size in millions. See Appendix D for a discussion of log scales.

## Analyze the Figure

- How would you describe the pattern of change?
- How much did population increase between year zero and 2000?
- This graph ends in the year 2000. What do you predict is the population today? Check your prediction.

Human population growth is not the same everywhere. In some nations, birthrates may be similar to death rates, as people decide to have fewer children and can act on that decision. In other nations, birthrates may be high for cultural reasons and because the children may be contributing to the income of the family. In countries with no programs to care for the elderly,

having children may be a critical strategy to surviving later in life. In some countries, women may also have less access to methods for limiting the number of children they have.

Carrying capacity for non-human species is usually studied in specific populations rather than across the entire range of the species. Because humans can transport resources great distances, it may be more useful to consider the entire human species in thinking about carrying capacity. For example, the population of Manhattan certainly consumes more food than is grown there, but death due to starvation is very rare in Manhattan. Conversely, people in some parts of the world may starve while crops grown in their region are shipped to other areas.

Does Earth have a carrying capacity for humans? Of course there is some limit, but where it is depends on many assumptions. For example, if everyone used fewer resources, the carrying capacity could potentially be higher. If we destroy some resources, it will be lower. A more even distribution of resources would also lead to a larger carrying capacity.

**Check Your Understanding**

- What factors might limit human populations?
- Why are assumptions important in predicting Earth's carrying capacity for humans?

# Key Concepts

- A population is all the individuals of one species in a given place.
- Populations vary due to reproduction, death, and movement in and out of an area.
- Without constraints, populations grow geometrically or exponentially.
- Growth of populations is limited by factors that can include lack of resources, disease, predation, buildup of wastes, and natural disasters.
- The number of individuals that an area can support is called the carrying capacity. Populations that increase above the carrying capacity tend to decline rapidly.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately interpret models of changes in population size*
2. *Make and defend valid predictions of future population size*
3. *Propose reasonable explanations of patterns in population size*

1. Imagine that a small national park was created to preserve elephants in an African nation. Ancient art shows that elephants lived in the area long ago, but illegal hunting for ivory nearly exterminated them. With some protection from the government, numbers started to recover. In the early 1980's the government began giving local people good-paying jobs protecting the elephants and developed tourism that supported many other

community members. Researchers began tracking elephant numbers to monitor the health of the population (Figure 23).

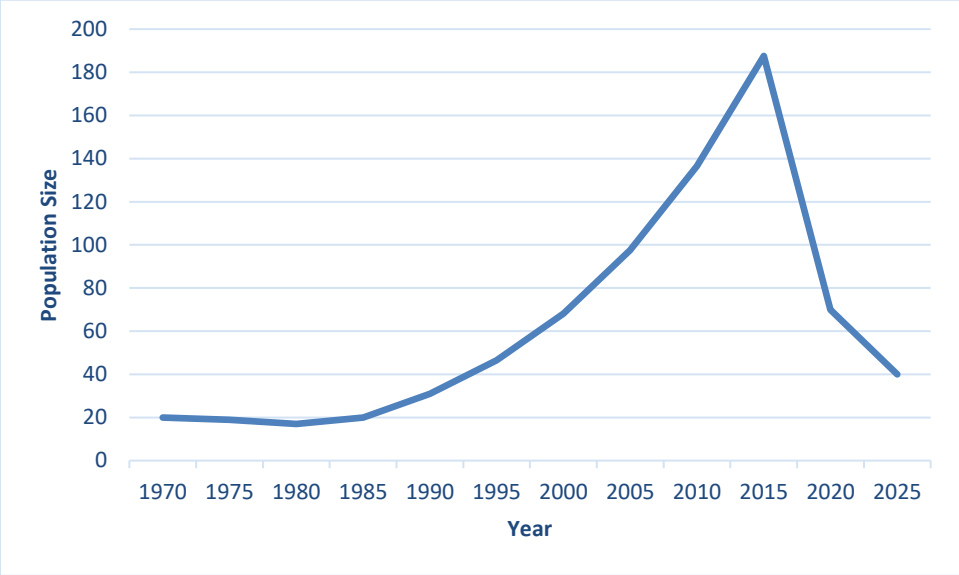



Figure 23. Hypothetical population of elephants.

A. When was there exponential growth. *(Learning Outcome 1)*
B. Explain possible reasons why the growth rate was exponential at this time. These are inferences. Use evidence to support them. *(Learning Outcome 3)*
C. Using population ecology concepts, explain why the population may have dropped, even though the elephants were still being protected *(Learning Outcome 3)*
D. What do you think the carrying capacity of this reserve is for elephants? Explain your inference and provide evidence. *(Learning Outcome 3)*

2. As you know:

$N_1 = N_0 + b – d$

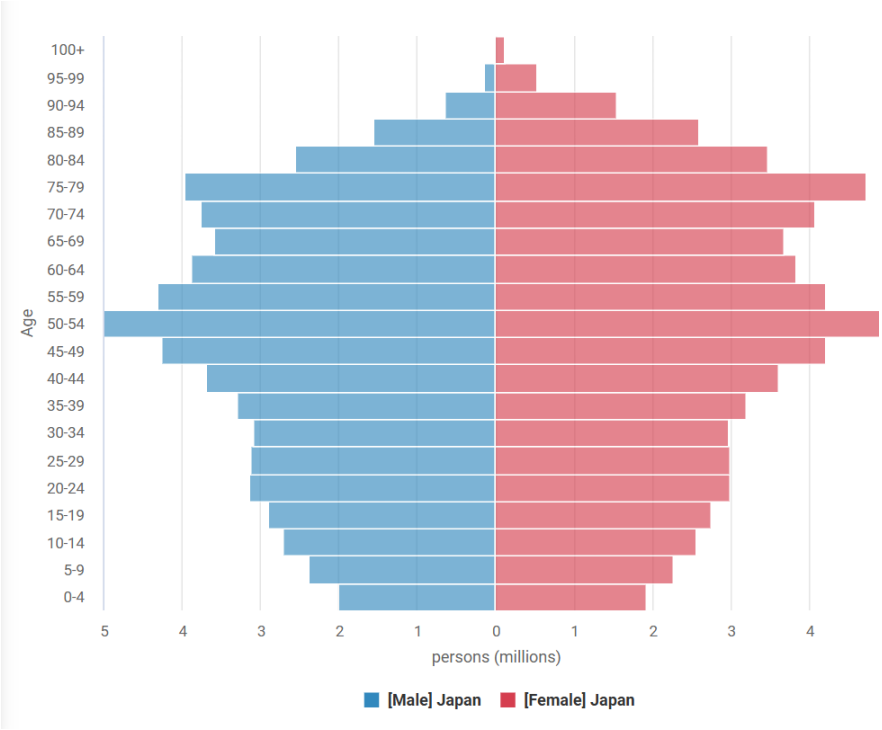
$N_1$ = Number of individuals next year
$N_0$ = Number of individuals now
b = The number of births
d = The number of deaths

Assume that:
There were 100 elephants in 2005
The birth rate is 0.25 per elephant
The death rate is 0.1 per elephant

A. Predict how many elephants there were in 2006, according to this model. *(Learning Outcomes 1 & 2)*
B. Evaluate this prediction. Are the assumptions of the model valid for this population? Why or why not? Explain your answer. *(Learning Outcomes 1 & 2)*

3. Refer to Figure 24.

4.




https://population.un.org/dataportal/data/indicators

Figure 24. Population pyramid for Japan in 2020.

A. What patterns do you see in the relative numbers of males and females? How would you explain these patterns? (*Learning Outcome 3*)
B. Compare the population pyramid for the US in 2020 (Figure 20) with the population pyramid for Japan in 2020 (Figure 24). Explain some possible reasons for differences or similarities. (*Learning Outcome 3*)
C. What do you predict will happen to the population of Japan in the next 20 years? Explain your prediction. (*Learning Outcome 1 & 2*)

**Unit IV: Populations**

# Chapter 13: Investment in Offspring

## Case Study Part 1: Saving Galapagos Tortoises by Understanding Their Survivorship

Burton, 2013

Figure 1. Young Galapagos tortoises (*Chelonoidis nigra*) in a reserve. The growth rings on the shell show the age of the animals.

The tortoises of the Galapagos Islands (Figure 1) can weigh up to 250 kg and can live for over 150 years. Females lay several eggs at a time and may lay up to 4 sets of eggs a year. Hard shells protect adult tortoises from predators. The tortoises can eat a wide variety of plants, so they might seem to have plenty of food. Despite these advantages, Galapagos tortoises have become extinct on some islands and are still in danger of extinction on others.

Some threats are obvious. The Galapagos Islands are about 1000 km (600 miles) off the coast of Ecuador. For centuries, ships stopped at the islands for water and food. Tortoises could be killed right away or kept alive in ships for many months until their meat was needed. As humans started to move to the islands, they continued to hunt tortoises and cleared tortoise habitat to make farms and towns. Settlers brought many species with them, including dogs, cats, rats, cows, goats, and pigs. The introduced predators eat eggs and young tortoises. The larger animals, such as cows, crush young turtles by stepping on them. Goats eat much of the vegetation on some islands, leaving little for the tortoises.

It might seem easy to preserve a species that can lay dozens of eggs a year and live over a century. But conserving habitat and protecting tortoises from hunting did not lead to much increase in tortoise populations. To really understand how to protect the tortoises, ecologists had to understand a tortoise's chance of surviving each stage of its life—its pattern of **survivorship**. Then they could concentrate resources on protecting tortoises at the most critical time.

Researchers followed some tortoises from hatching and captured many of various ages. They marked animals, measured them, and counted growth rings on their shells to learn their patterns of growth. They collected dead tortoises and recorded when and—if possible—how they died. In this chapter, you will learn more about how survivorship is analyzed, then discover how this information helped to increase Galapagos tortoise populations.

**Learning from the Case Study**

- What is survivorship?
- How could an animal that lives over 100 years and produces dozens of eggs a year be in danger of extinction?
- Why did researchers have to know which age groups had low survivorship?
- How did researchers measure survivorship?

# Learning Outcomes

1. *Accurately describe and explain different patterns of survivorship*
2. *Correctly identify relationships between survivorship, reproductive investment, and environmental factors*
3. *Make reasonable predictions of future population trends based on population structure and fecundity patterns*
4. *Compare life history patterns between species, making valid inferences about differences and similarities*

**Vocabulary Toolkit**

**Word Watch List**

**Survivorship**: Living until the next age category, usually stated as a proportion of a population
**Gestation**: pregnancy
**Fecundity**: production of offspring
**Mortality**: Death, usually stated as a proportion of a population dying
**Cohort**: Group of individuals produced at the same time
**Life expectancy**: Average number of additional years an animal of a given age will live
**Survivorship curve**: Line chart showing the number of individuals surviving to each age
**Life history strategies**: Patterns of survival and reproduction that include the number of offspring and the investment per offspring. No conscious choice by the organism is implied
**r-selected**: Species with a high reproductive rate and low investment in each offspring. Lifespan is usually short, and juvenile mortality is usually high
**K-selected**: Species with a low reproductive rate and high investment in each offspring. Lifespan is usually long, and juvenile mortality is usually low

**Why Do Lifespan and Reproduction Vary so Much?**

Coconut palm trees live for over a century and produce fewer than 100 fruits per year, while the tiny mouse-ear cress—a flowering plant—goes from sprouting to producing 10,000 seeds in 3 to 6 weeks (Figure 2). A huge African elephant has a **gestation** period (conception to birth) of 22 months and may live for decades. Tiny brine shrimp live for a year. They have a high **fecundity**, laying thousands of eggs (Figure 3). Why do different species have such different patterns in longevity and fecundity?

**A**

http://simple.wikipedia.org/wiki/Coconut_palm

**B**

https://en.wikipedia.org/wiki/Arabidopsis_thaliana

Figure 2. **A**. Coconut palm trees (*Cocos nucifera*) can live a long time and produce few large seeds. **B**. Mouse-ear cress (*Arabidopsis thaliana*) plants have a short life span and produce many tiny seeds.

**Analyze the Figure**

- Note the size difference between these plant species. Do you think size is related to lifespan?
- Look at the size of the seeds (coconuts) of the coconut palm tree. Do you think a tree could produce hundreds of them at a time?
- Which of these plants seems more likely to survive a violent storm?

**A**

http://commons.wikimedia.org/wiki/File:Live_brine_shrimp.jpg

**B**

Burton, 2009

Figure 3. **A**. Brine shrimp (*Artemia salina*) have short lives and lay thousands of eggs. Adults can be about 10 mm long. **B**. African elephants (*Loxodonta africana*) are pregnant for almost two years, then groups of related females care for their offspring for years as they grow up. Adults can be 2.5 - 3.5 m tall (males are larger).

You may have already noticed that larger species tend to live longer. For small species, the environment may be more variable and dangerous. A tiny plant can be crushed with one step of an elephant, while a giant baobab tree may be able to survive decades of elephant damage. Small species may have more difficulty travelling to areas where food is more available or escaping various threats.

Researchers examined several factors that might influence longevity in birds and mammals. They separated out species that could fly (Figure 4). Flight may allow animals to flee predators, storms, areas with low food availability, and other potential dangers. The researchers also found other behaviors that decreased vulnerability also led to longer lifespans.

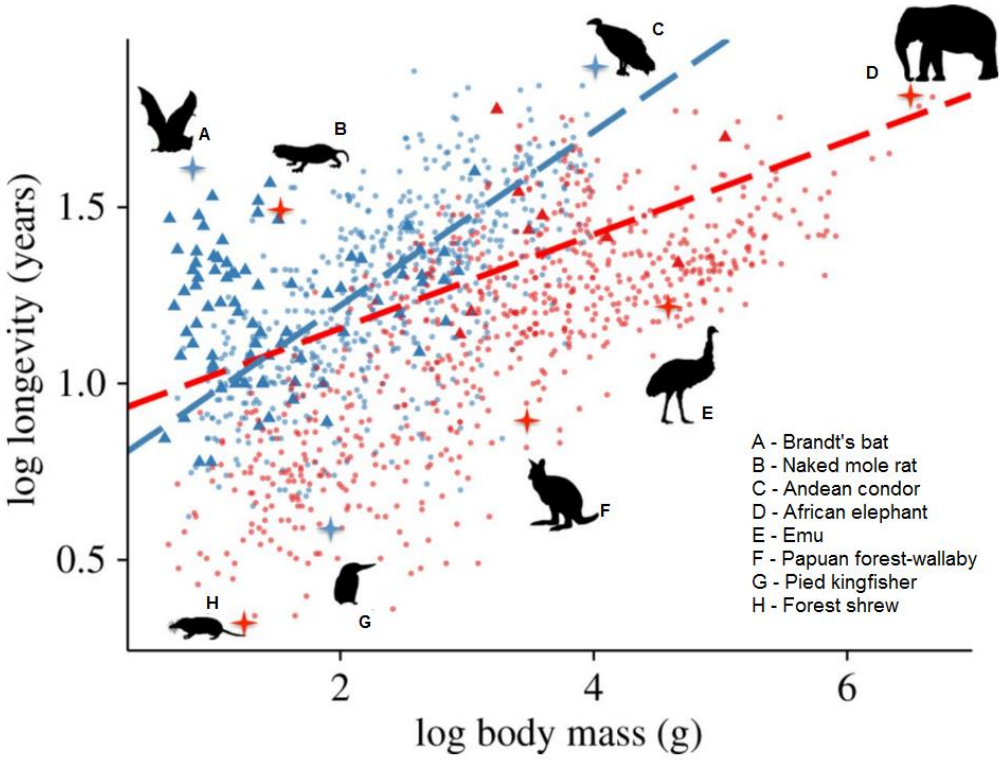



Figure 4. Relationship between body size and longevity for 1368 species of birds and mammals. Blue markers and lines = flying animals (bats are triangles). Red markers and lines = non-flying (flightless birds are triangles). Stars mark data points for species with letters and silhouettes. Modified from: Healy, K., Guillerme, T., Finlay, S., Kane, A., Kelly, D. Donahue, I, McClean, D., Jackson, A. & Cooper, N. (2014). Ecology and mode-of-life explain lifespan variation in birds and mammals. *Proceedings of the Royal Society of London B: Biological Sciences*, *281*(1784), 20140298.

**Analyze the Figure:**

- Do larger birds and mammals tend to live longer? Support your answer with evidence.
- Identify a species that has a longer lifespan than one would predict based on its size.
- Identify a species that has a shorter lifespan than one would predict based on its size.
- Which group—flying or non-flying—had a greater increase in longevity as body mass increased? Explain your reasoning.

For non-flying species, living underground or foraging in trees led to greater longevity. For example, naked mole rats spend almost their entire lives underground. They live much longer than other mammals their size. They raise young cooperatively, with only one female in the colony giving birth to all the offspring. Flightless birds, such as the emu, tend to have short lifespans for their body size.

Flying species had greater longevity if they were active at night or during the day, rather than at dusk and dawn. For example, North American bats fly and are active at night. They live much longer than other mammals their size, such as mice. Perhaps this is because the only way bats can produce several offspring is to live several years. Bats cannot carry multiple young during pregnancy because they would be too heavy.

Larger species may tend to live longer because it takes a long time to produce a large offspring and for large individuals to grow to their mature size. A short lifespan would be a selective disadvantage in a species that took a long time to reproduce.

Another mechanism that could reduce lifespan would be a buildup of toxins produced in metabolism. Producing ATP creates oxidants and free radicals that can damage biomolecules. Smaller bodies have a greater surface to volume ratio and lose heat faster than larger bodies. So smaller endothermic animals may need to produce more heat, requiring faster metabolic rates. Organisms with faster metabolic rates would produce more wastes for a given period, damage their own tissues more, and die younger than those with slower metabolic rates.

**Check Your Understanding**
How are size and lifespan related?
How are lifespan and reproductive rate related?

**Ecologists Track Survivorship Patterns**

Living things may be born, hatched, sprouted, or created by division, but they all die. When and how they die vary. Ecologists study the pattern of individual survival to understand survivorship patterns in populations. A **cohort** is a group that started out at the same time. Researchers can follow cohorts through time to track survivorship at a specific age. They can also combine data from several years to track survivorship, but each year might have a different pattern. For more on this topic, see **Taking it Further: Cohort and Static Life Tables**.

Ecologists in Britain put bands on northern lapwings (Figure 5) just before the birds left the nest. They collected bands from dead birds to determine the age the birds died and organized the information into a life table to show patterns in survivorship (Table 1). Birds that hatched the same year were in the same cohort. Multiple cohorts were studied. Birds in age category 1 died during the calendar year in which they were banded. Birds in age category 2 died in the calendar year after the year they were banded, and so on. Data from banded birds allow researchers to calculate the risk of dying before reaching the next age.

http://commons.wikimedia.org/wiki/File:Vanellus_vanellus_-_Northern_Lapwing.jpg

Figure 5. Northern lapwing (*Vanellus vanellus*).

Table 1. Life table for northern lapwings (*Vanellus vanellus*). Data based on Lack (1950) as reported in: Haldane, J.B.S. (1953). Some animal life tables. *Journal of the Institute of Actuaries*, 83--89.

| Age Interval | Number of Interval (x) | Number Alive at Beginning of Age x ($n_x$) | Number Surviving to Next Age Interval ($n_{x+1}$) | Proportion Alive at Start of Interval ($l_x$) | Number Dying During Interval ($d_x$) |
|---|---|---|---|---|---|
| 0-1 | 1 | 593 | 395 | 1 | 198 |
| 1-2 | 2 | 395 | 261 | 0.666 | 134 |
| 2-3 | 3 | 261 | 171 | 0.440 | 90 |
| 3-4 | 4 | 171 | 120 | 0.288 | 51 |
| 4-5 | 5 | 120 | 72 | 0.202 | 48 |
| 5-6 | 6 | 72 | 49 | 0.121 | 23 |
| 6-7 | 7 | 49 | 28 | 0.083 | 21 |
| 7-8 | 8 | 28 | 19 | 0.047 | 9 |
| 8-9 | 9 | 19 | 13 | 0.032 | 6 |
| 9-10 | 10 | 13 | 8 | 0.022 | 5 |
| 10-11 | 11 | 8 | 2 | 0.013 | 6 |
| 11-12 | 12 | 2 | 1 | 0.003 | 1 |
| 12-13 | 13 | 1 | 1 | 0.002 | 0 |
| 13-14 | 14 | 1 | 0 | 0.002 | 1 |
| Over 14 | 15 | 0 | 0 | 0 | 0 |

**Analyze the Table**

- Of the 593 birds alive at the start, about how many made it to 1 year of age?
- How old was the oldest northern lapwing in the study?
- What proportion of the birds survive to age 8 ($l_8$)?

Northern lapwings have about a 67 % chance of surviving to their first year ($l_2$=395/593 = 0.666, or 67 %). This also means they have a 33 % chance of **mortality** (dying) in their first year (100 % - 67 % = 33 %). Survivorship gradually falls over time. The maximum **life expectancy** for the lapwings would be 14 years. The average life expectancy is the average amount of time an individual can expect to live, based on its current age (see **Taking It Further: Calculating Life Expectancy**).

**Taking it Further: Cohort and Static Life Tables**

Life tables can be constructed from the data on one cohort. For example, the northern lapwings were followed from fledging until death. Cohort life tables are also called dynamic life tables because they change depending on which cohort is being followed. For example, one year may have a much lower survival of juveniles than other years due to weather, disease, predation, or other factors. Separate life tables for different cohorts can reveal important differences in survivorship at different times.

The data for cohort life tables may take years—even centuries—to collect for long-lived species. Tagging and following individuals may be extremely difficult. As a result, life tables may be based on a "snapshot" in time. For example, a researcher may count the number of individuals in each age category and build a life table that assumes the age structure at that time is similar to what it would be at any time. This type of table is called a static life table because it is based on one point in time and does not show variations in a population's age structure over time. One famous life table is based on Dall sheep skulls collected in Alaska. These animals live on rocky slopes in areas that are almost impossible to reach during the winter. Following a cohort would be extremely difficult. Instead, an ecologist used skulls to determine the age of the individuals when they died by looking at teeth and horns. In static life tables the influence of one unusual year may be balanced by the data from several other years.

**Taking It Further: Calculating Life Expectancy**

A life history table can be used to calculate life expectancy. In the famous book, *A Sand County Almanac*, Aldo Leopold reported data he collected by putting leg bands on chickadees. Leopold banded the birds in early winter. Chickadees are easy to trap, so he assumed that he was trapping all the birds that had hatched that spring. He also assumed that any birds not trapped the next year had died. Recall that all of the birds that hatched the same year are a cohort. Leopold banded 67 birds during their first winter when they were about 0.5 years old. Only 19 survived to age 1.5, 7 survived to 2.5, 3 survived to 3.5, and one bird made it to 4.5 years old. This information can be used to make a life table (Table 2).

Table 2. Partial life table showing survivorship in chickadees (*Poecile atricapillus*). Data from: Leopold, A. (1989). *A Sand County almanac, and sketches here and there*. Oxford University Press. Photo: http://en.wikipedia.org/wiki/Black-capped_chickadee#mediaviewer/File:Poecile-atricapilla-001.jpg.

| Age | Cohort (x) | Number alive in the middle of the time interval ($L_x$) | Number alive at the start of the time interval ($n_x$) |
|---|---|---|---|
| 0-1 | 0 | 67 | |
| 1-2 | 1 | 19 | |
| 2-3 | 2 | 7 | |
| 3-4 | 3 | 3 | |
| 4-5 | 4 | 1 | |
| 5-6 | 5 | 0 | |

The variable $L_x$ means the number of individuals alive in the middle of cohort x. So $L_1 = 67$, $L_2 = 19$, and so on. Another way to write "the number alive in the middle of the cohort after cohort 1" is $L_{1+1}$ or $L_2$. This is not the same thing as $L_1 + 1$.

The number of animals that will be alive at the beginning of the interval is $n_x$. $L_x$ is halfway between $n_x$ and $n_{x+1}$. How do you estimate how many chickadees were alive at the *beginning* of a cohort? Hint: If I said the winning lottery ticket were halfway between 50 and 100, how would you figure out the winning number? You would add up the starting number and the ending number and divided by two. For example:

$$L_x = \frac{n_x + n_{x+1}}{2}$$

We can rearrange this to calculate the number alive at the beginning of interval x:

$$n_x = 2L_x - n_{x+1}$$

**Continued**

**Taking It Further: Calculating Life Expectancy, cont.**

We need to know how many were alive at the start of the next interval to solve this. Fortunately, we know the value of $n_5$, which is also $n_{4+1}$. It's 0.

$$n_4 = 2L_x - n_5$$

If we fill in the values from the table, we get:

$n_4 = 2(1) - 0$, which is 2.

Now we have a value for $n_{3+1}$. Work backwards to fill in the table.

Table 3. Survivorship, mortality, and life expectancy in chickadees. Fill in the missing values.

| Age | Cohort x | # Alive in middle Lx | # Alive at start nx | # Dying dx | Probability of dying qx | Probability of surviving sx | Total years to live Tx | Life expectancy ex |
|---|---|---|---|---|---|---|---|---|
| 0-1 | 0 | 67 | 106 | 78 | 0.74 | | | 0.92 |
| 1-2 | 1 | 19 | | | | 0.36 | 30 | |
| 2-3 | 2 | 7 | 10 | 6 | 0.6 | | 11 | 1.1 |
| 3-4 | 3 | 3 | 4 | 2 | 0.5 | 0.5 | 4 | 1 |
| 4-5 | 4 | 1 | 2 | | | | 1 | |
| 5-6 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

To calculate the number that died in a certain interval, we take the number alive at the start of an interval and subtract the number alive at the start of the next interval:

$$d_x = n_x - n_{x+1}$$

For example, $d_3 = n_3 - n_{3+1}$ or $d_3 = 4 - 2 = 2$

What is the probability of dying between any two intervals? The number who died during the year divided by the number who were alive at the start of it:

$$q_x = \frac{d_x}{n_x}$$

What is the probability of dying between interval 3 and interval 4?

$$q_3 = \frac{d_3}{n_3}$$

$$q_3 = \frac{2}{4} = 0.5$$

**Continued**

**Taking It Further: Calculating Life Expectancy, cont.**

The probability of surviving would be the inverse of the probability of dying:

$$s_x = 1 - q_x.$$

So $s_3 = 1 - 0.5 = 0.5$

For each cohort, how many animals ($L_x$) did we find that were that age *or older*?

(Add $L_x$ for each cohort *and* the ones below it.) This is the number of animal-years left to live ($T_x$). Fill in the values.

If there is $T_x$ time left, and each of the animals starting in that cohort ($n_x$) has an equal chance at those years, life expectancy ($e_x$) the number of years, on average, an animal entering that cohort has left is calculated as:

$$e_x = \frac{T_x}{n_x}$$

For a chickadee in time interval 3, this would be:

$$e_3 = \frac{T_3}{n_3} \qquad \text{or} \qquad e_3 = \frac{4}{4} \text{ or } 1$$

A chickadee that is 3 years old will live, on average, one more year. Of course, some individuals will live more or fewer years than the average.

Fill in the missing values in the life history table. Notice that life expectancy will go up after an age when mortality is high because the individuals have survived a risky time.

**Model Skill: Line Graphs**

Line graphs are used most often to show changes in time. Time is on the X-axis and the changes in the value of the variables are shown on the Y-axis. Regular time intervals are connected with a line. If some time intervals are missing, the line should break to make this obvious.

Create a graph that shows the proportion of the original northern lapwings surviving at each age interval using the blank line graph (Figure 6). The values for survivorship ($n_x$) are the number of birds that survived to the start of that time interval divided by the total number of banded nestlings. All of the individuals are alive at the start, so $l_x = 1$ at time interval one ($l_1$). Put a dot on the graph at that value (1) above the label 1. At the next age interval the value for proportion surviving was about 0.67, so put a dot above age interval 2 that is a bit below 0.7. Do this with all of the remaining categories. When you have done this, connect the dots with a line. This graph shows the safer and riskier stages of a northern lapwing's life.

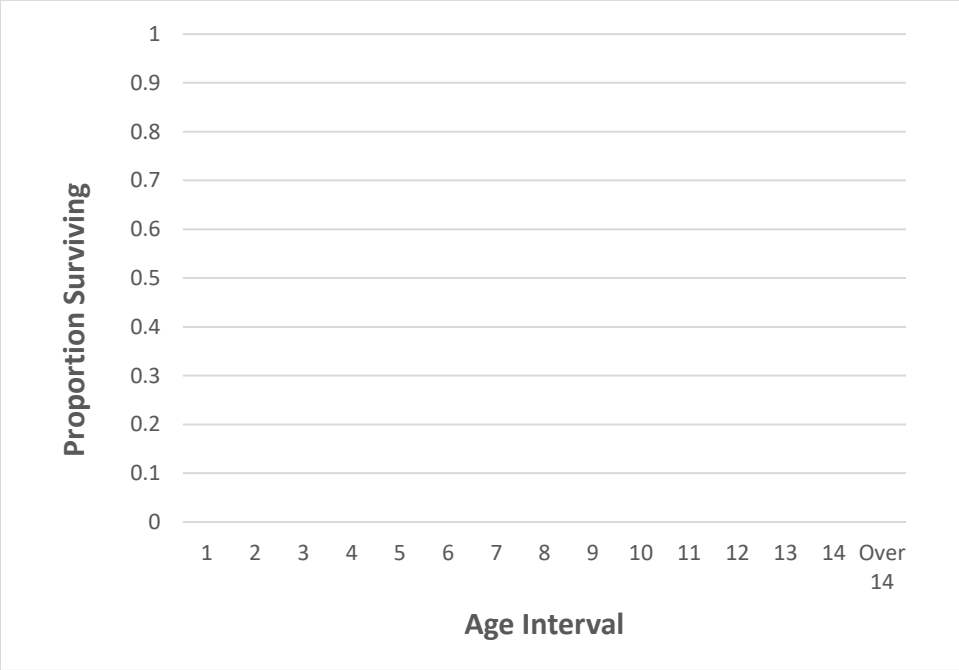



Figure 6. A line graph showing proportion surviving at each age interval for northern lapwings. Fill in the values from $l_x$ in Table 1.

**Survivorship Curves Show Risk of Dying**

We can use the data from Table 1 to create a graph that shows how many northern lapwings were alive at the beginning of each age interval (Figure 7). There were 593 alive at the start, but this number decreased each year until the maximum age of the birds. This is a **survivorship curve**. It gives us an idea about the risk of death at each stage of a Northern lapwing's life. A steep slope between age categories shows high mortality/low survivorship.

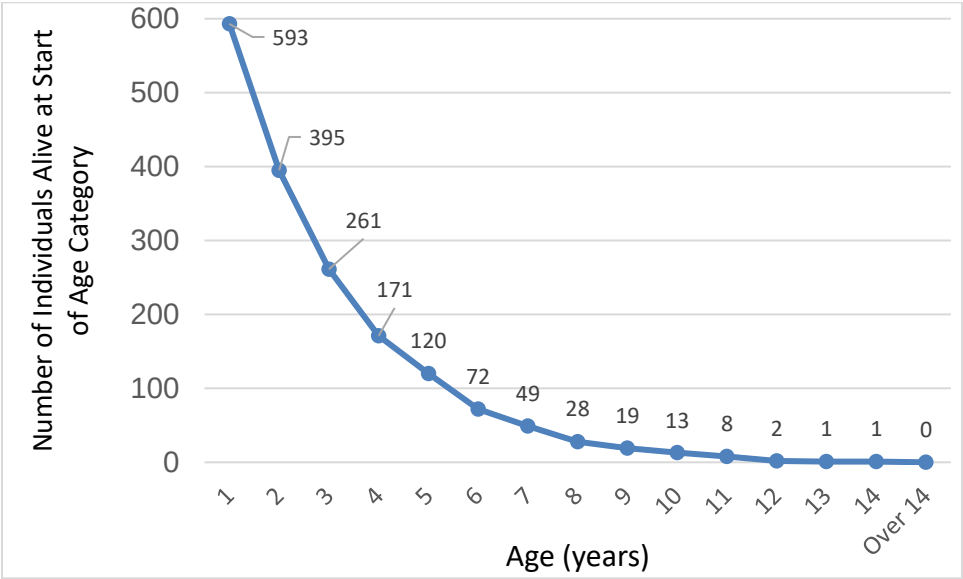



Figure 7. A survivorship curve for northern lapwings.

**Analyze the Figure**

- How many of the birds survived to age 10?
- What age seems particularly dangerous for the birds (look for a steep drop)?
- Approximately what percentage of the 2-year-old birds survived to age 3?

To standardize the curves for many species, ecologists usually calculate the percent mortality and set the starting number of individuals to 1,000. Many curves show a geometric or exponential decline. A difference of a few individuals is difficult to see when the maximum value is 1,000. This doesn't matter when there are many individuals, but it is important when there are only a few. To solve this problem, it is common to use a log scale. Each of the major intervals is 10 times as big as the one below it. It starts at 1 on the bottom and goes up by ones. Then at 10, it goes up by tens. At 100, it goes up by hundreds. This makes the loss of the last few individuals as easy to see as the loss of many individuals in the first year (Figure 8; for more on log scales, see Appendix D). Because the Y-axis uses a log scale, the decline looks like a straight line from age zero to 10.

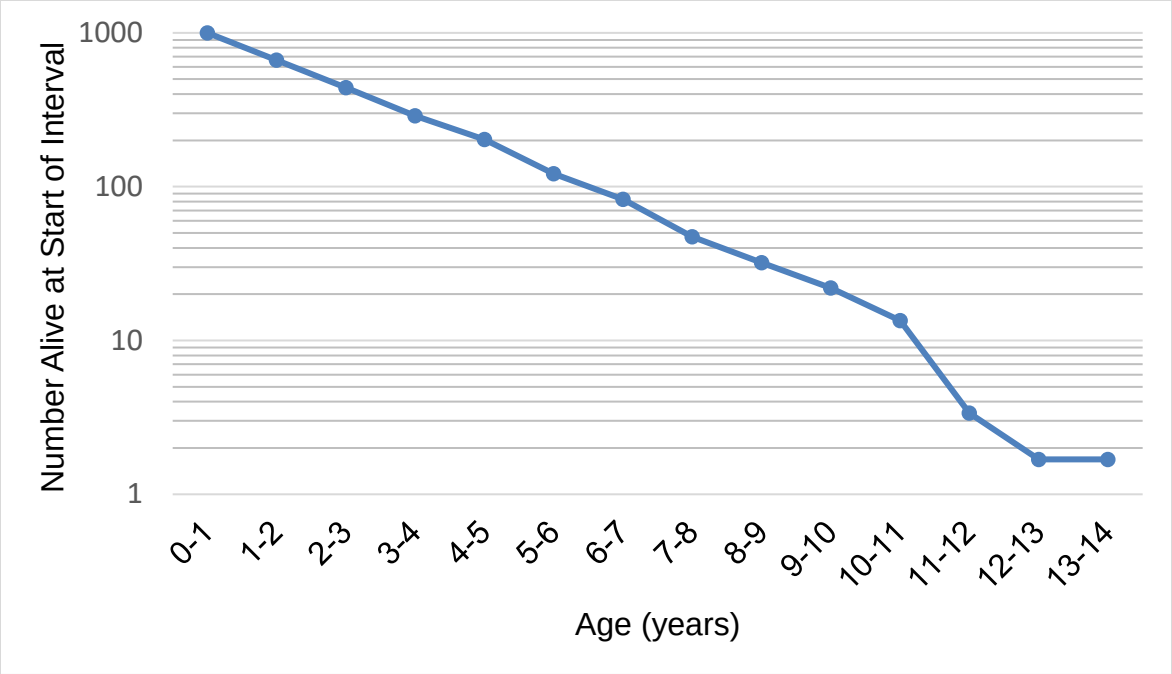



Figure 8. Survivorship curve for northern lapwings. The number alive ($n_x$) for each age is plotted on a log scale. By convention, numbers have been adjusted as if the study had started with 1,000 individuals. Log scales do not go to zero because $10^0 = 1$.

**Analyze the Figure**

- If 1,000 birds had been alive at the start, about how many would have made it to 1 year of age (age interval 1-2)?
- What is the approximate probability that a hatchling (the number at the start of the first age interval) will survive to reach the 5–6-year age range?
- When do you think the birds are dying of old age?

**Check Your Understanding**

- If you know the mortality at a specific age, how could you calculate survivorship for that age?
- What does a steep slope in a survivorship curve indicate?
- Why is a log scale used for most survivorship curves?

**Survivorship Curves Differ Between Species**

Trumpet trees are native to tropical areas. Compare the trumpet tree survivorship curve in Figure 9 with the curve for northern lapwings (Figure 8). Note that the trumpet-tree curve starts at 10,000 seeds produced. Germinating (sprouting) seeds start at 1,000. The sprouts are arguably a better comparison to hatchlings than the number of seeds produced because the number of unhatched eggs was not counted.

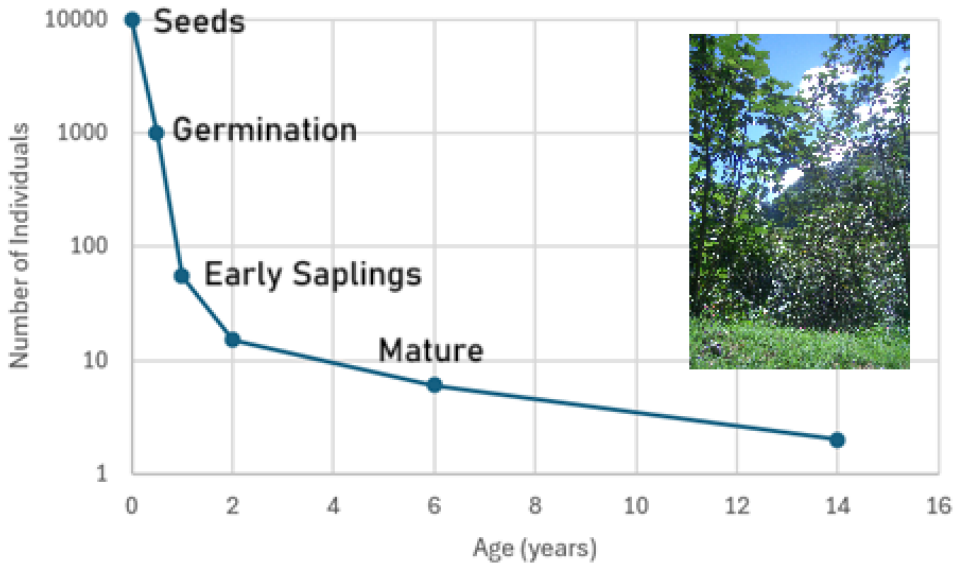



Figure 9. Survivorship curve for trumpet trees (*Cecropia peltata*). Based on: Silander, S.R., & Lugo, A.E. (1990). *Cecropia peltata* L. Yagrumo hembra, trumpet-tree. *Silvics of North America Volume 2. Hardwoods. Agriculture. Handbook*, 654, 244-249. Photo: https://upload.wikimedia.org/wikipedia/commons/e/ef/Cecropia_peltata_El_Yunque_National_Forest.jpg

**Analyze the Figure**

- Of the 1,000 seeds that germinated (sprouted), about how many survived 1 year to become established seedlings?
- How old were the oldest trumpet trees in the study?
- Approximately how many trees survived to age 6?

Does the survivorship curve for trumpet trees have the same shape as the one for the northern lapwings? A curve for some other tree species might be similar in shape, but different in scale. For example, a palm tree will not mature until it is about 75 years old.

African elephants have long life spans, late sexual maturity, and long periods of maternal care. Compare the survivorship curve for female elephants (Figure 10) with the others. How is the shape of this survivorship different from the shapes other survivorship curves in this chapter?

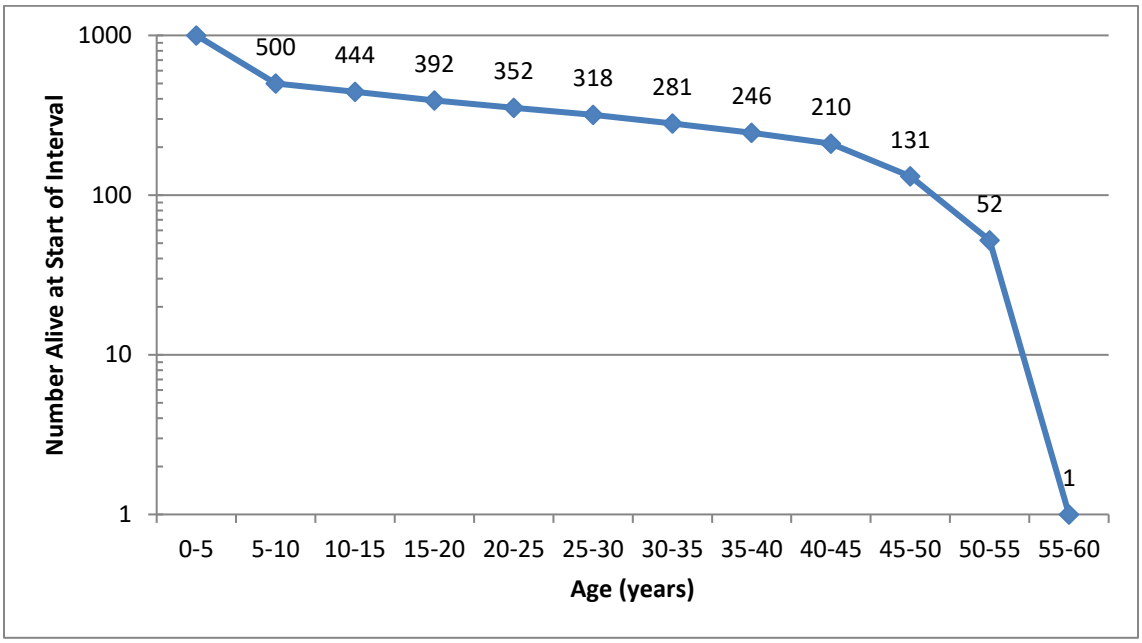
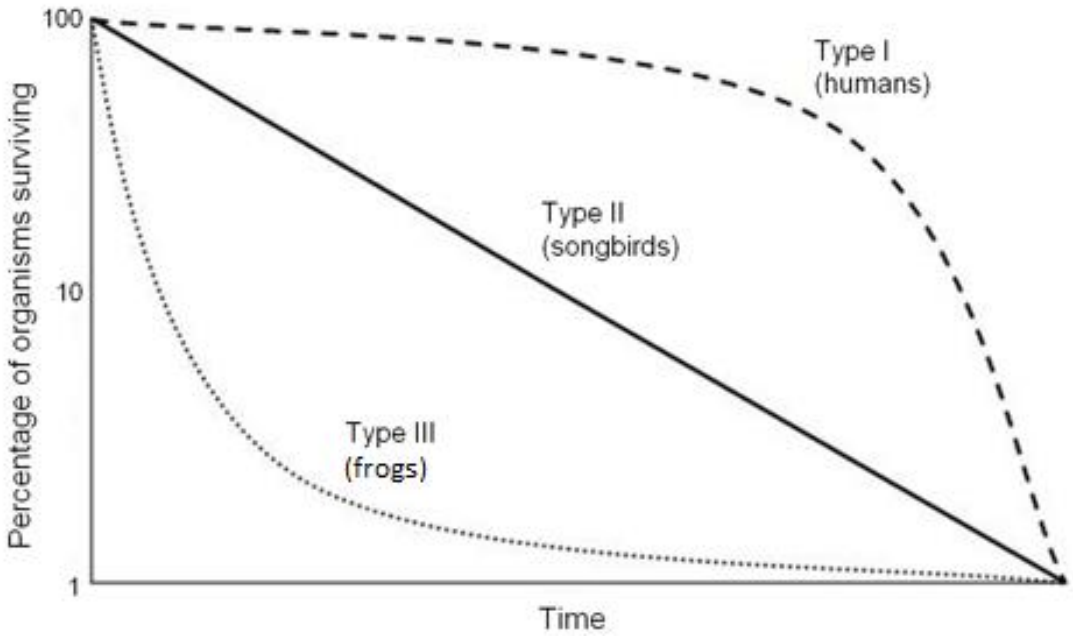



Figure 10. Survivorship patterns for female African elephants (*Loxodonta africana*). Logarithmic scales do not go to zero. Based on data from Armbruster, P. and Lande, R. (1993). A population viability analysis for African elephant (*Loxodonta africana*): How big should reserves be? *Conservation Biology*, 7:602-610.

**Analyze the Figure**

- At what age is female elephant survivorship lowest?
- At what ages is female elephant survivorship fairly constant?
- What is the maximum life span for female elephants?

We can group these types of curves into three different categories (Figure 11). In type I, as with the elephants, survivorship is fairly steady until old age. In type II, as in the northern lapwings, survivorship is generally constant throughout life. In type III, as in the trumpet-trees, there is very high juvenile mortality, but survivorship is then fairly steady until old age. These are all models of different types of survivorship. None of the actual curves are a perfect fit, but the models allow us to make useful generalizations. Survivorship patterns can also vary for the same species under different conditions. To see how human survivorship curves have changed over time, see **Why It Matters: Survivorship Patterns and Quality of Life**.




Modified from: http://upload.wikimedia.org/wikipedia/commons/c/c4/Survivorship_Curves.jpg

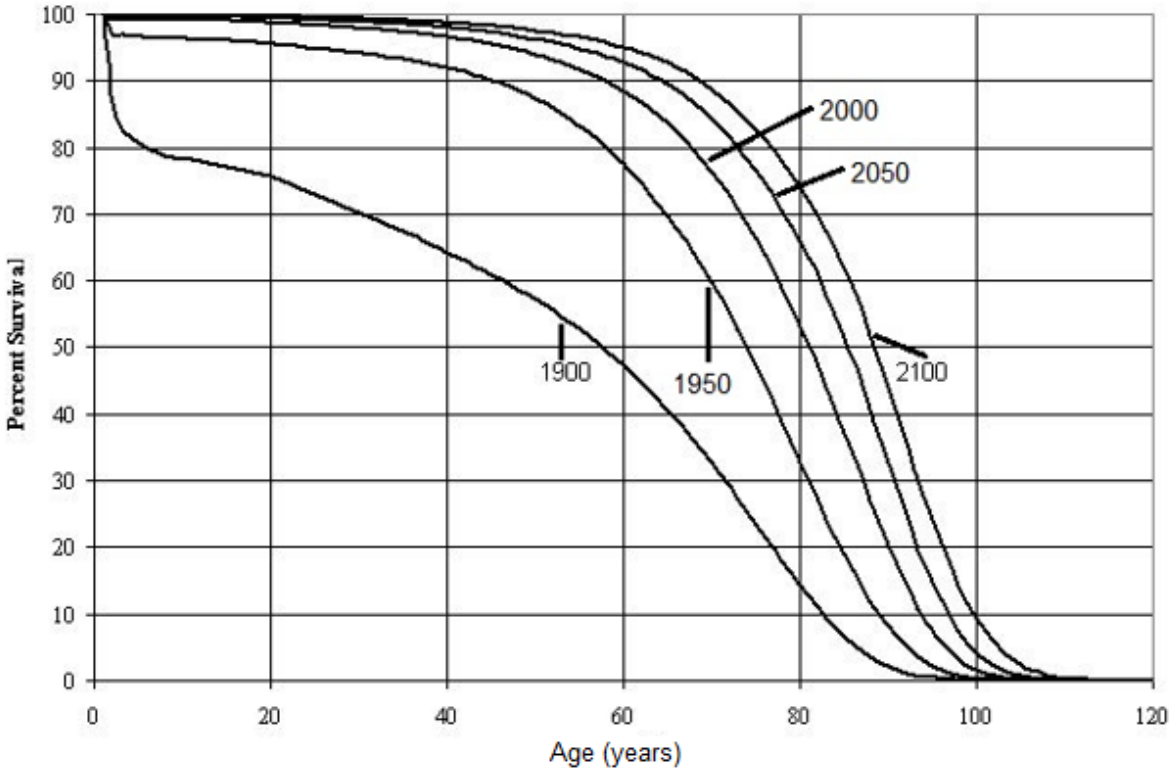
Figure 11. Three shapes of survivorship curves. Survivorship is plotted on a log scale. Curves are smoothed.

**Analyze the Figure**

- Which curve shows a rapid die-off of young?
- Which curve shows very little die-off until old age?
- Which curve shows a steady mortality rate?

**Why It Matters: Survivorship Patterns and Quality of Life**

Survivorship patterns in humans can reveal health and quality-of-life issues. Examine human survivorship trends and predictions in the United States (Figure 12). Consider variables that influence human mortality and how those variables may have changed between 1900 and 1950 or between 1950 and 2000.




Modified from: http://www.ssa.gov/OACT/NOTES/as120/LifeTables_Body.html

Figure 12. Human survivorship curves for the United States. Each line is for a specific year. The first three lines are for 1900, 1950, and 2000. The last two are projections (the results of assumptions and calculations) for 2050 and 2100.

**Analyze the Figure**

- How does the trend for 1900 differ from the trend for 1950?
- What do these curves reveal about changing quality of life in the US?
- What medical, political, economic, cultural, and ethical issues are involved in changing human survivorship patterns?

**Case Study Part 2: Survivorship Analysis Helps Preserve Tortoises**

https://commons.wikimedia.org/wiki/File:Gigantic_Turtle_on_the_Island_of_Santa_Cruz_in_the_Galapagos.JPG

Figure 13. A species of Galapagos tortoise (*Chelonoidis nigra*).

Ecologists found that Galapagos tortoise eggs and hatchlings were attacked by rats. Young tortoises were often killed by dogs or died when cows stepped on them. This analysis of age-specific mortality showed that protecting the tortoises when they are small was critical. In response to the findings, rat poison was spread on some islands. Tortoises bred in reserves or collected as eggs are now kept safe until their shells are hard enough to resist damage from introduced species. These actions have led to increasing tortoise populations.

Young turtles were found on the island of Pinzón in 2015, two years after the rats were poisoned out. These hatchlings may have been the first to survive on the island in 150 years. If the conservation efforts had been delayed, there may have been no adult tortoises left to breed. Tortoises are also being protected on some islands by removal of introduced species such as goats and cats. The Galapagos tortoises still need protection, but understanding their survivorship patterns has made the preservation efforts much more effective.

**Learning from the Case Study**

- How did understanding survivorship patterns make the tortoise protection program more effective?
- Would creating more reserves for adult tortoises or banning all turtle hunting have led to a recovery of the tortoise population? Explain your prediction.
- What would be your next step if you were designing a program to protect the Galapagos tortoises? Compare your plan with a classmate's plan.

**Check Your Understanding**

- What can we learn from survivorship curves?
- What might make survivorship curves different between species?
- Would you predict that survivorship curves would always be the same for a species, or are they likely to be different in different places and at different times? Explain your reasoning.

**Producing Offspring Involves Trade-offs**

Individuals can increase their fitness by investing in reproduction at different times and different ways, these patterns of investment are called **life history strategies**. The word “strategy” does not mean that palm trees or robins think about how many offspring to have, and how much to invest in each one. It means that certain reproductive patterns lead to higher fitness than other patterns. These strategies might include when individuals reach reproductive age, how many offspring they produce, how much they invest in each offspring, and other factors. For single-celled species, the rate of cell division and whether the cells exchange DNA with other cells might be important strategies.

If there is a very high mortality for juveniles—a Type III pattern—an individual must produce many offspring to have any survive to reproductive age. Species with short lives and high maximum reproductive output are called **r-selected**. Recall from Chapter 11 that the variable r stands for per capita reproductive rate. An individual only has a certain amount of energy to invest in offspring. If it produces many offspring, it can only invest a little in each one. These "cheap" offspring have a high mortality. Investment in reproduction also leads to fewer resources for activities that could prolong an individual's life, such as mounting an immune response, making defensive chemicals, or repairing tissues. For more on the trade-off between reproductive output and lifespan, see **Evolutionary Perspective: The Cost of Reproduction**.

**Evolutionary Perspective: The Cost of Reproduction**

If fitness depends on leaving more offspring, why don't individuals produce as many offspring as they possibly can? As you might expect, maximizing reproductive output can come at a cost. Diverting energy and nutrients to producing eggs, for example, may mean a shorter life span for a female bird. This is a life history tradeoff.

The wild ancestor of the domestic chicken produces fewer than a dozen eggs per year. Domestic chickens have been artificially selected for various traits, including egg production. This variation in reproductive output allows us to analyze the effect of higher egg production on life span (Figure 14).

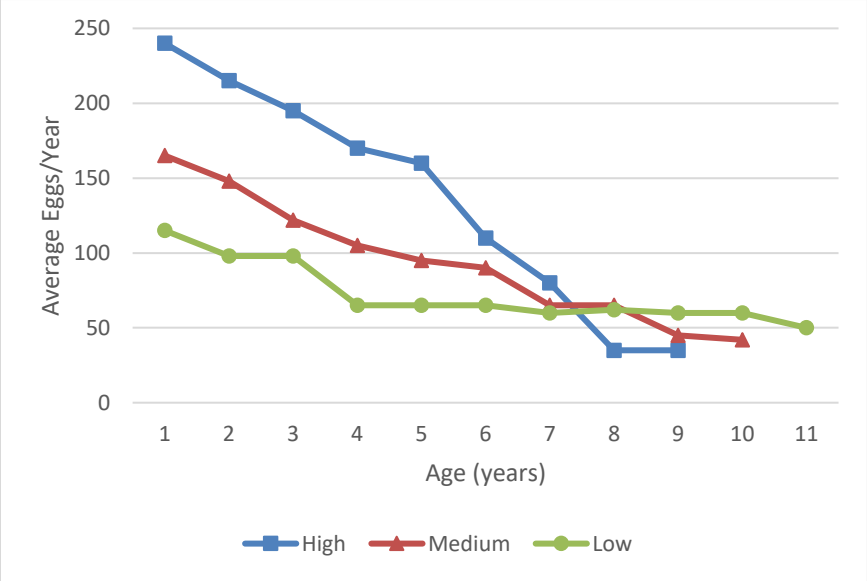



Figure 14. Tradeoffs between reproductive output (eggs laid per year) and age of domestic chickens from three different strains, high, medium, and low egg output. Based on: Pianka, E.R. 1999. *Evolutionary Ecology*. Benjamin Cummings. Adapted from Romanoff and Romanoff 1949.

**Analyze the Figure:**

- Which strain (high, low, or medium egg output) lived the longest?
- Which strain had the most decrease in laying with age?
- Why couldn't researchers compare age and egg-laying in species of wild birds or manipulate the amount of egg-laying in wild species?

This explanation may sound circular: high juvenile mortality leads to high reproductive rate, which leads to high mortality. However, the environment plays a major role in survivorship. A dangerous environment will favor selection for early reproduction. As noted earlier, the same environment may be much more dangerous for some species than others. Small species tend to

be more vulnerable to environmental risks. If the environment causes high mortality, having many offspring is a better strategy than having a few, high-quality offspring.

Invasive species are often r-selected. Their fast reproduction makes them hard to eliminate. Even if most of the individuals in a population are destroyed, the population quickly grows again. Because each individual can produce many offspring, these populations can increase very quickly. It is easy for them to overshoot carrying capacity, then crash. When they crash, the few individuals left behind can rapidly reproduce, leading to another cycle of increase and crash.

Tiny fruit flies (Figure 15) are a good example of an r-selected animal. They reach adulthood about two weeks after they hatch. Each female can lay about 20 eggs at a time and can breed several times. The flies live only a few months. This live fast, die young lifestyle has made fruit flies popular with biologists who study genetics. These flies can go through 10 generations in one year.

http://en.wikipedia.org/wiki/Drosophila_melanogaster#/media/
File:Drosophila_melanogaster_-_side_(aka).jpg

Figure 15. A fruit fly (*Drosophila melanogaster*).

Plants that we consider weeds are usually r-selected. They have many small seeds, grow quickly, and may live less than a year. They usually do not invest in deep roots or in woody tissue.

If an individual produces very few offspring, it can invest a lot of resources in each one. This investment may be in the form of stored food, as we see in the coconut produced by the coconut palm tree, or it could be in the form of years spent providing milk and care to a baby elephant after a long gestation period. This leads to high survivorship in the young (type I curve). Populations with slow growth tend to be fairly stable. They may overshoot carrying capacity, but only a little. It takes so long for the next generation to breed that disease, lack of resources, or other factors have time to reduce reproduction. Because so few animals die, there is a lot of competition to be a successful breeder. The large investment in each offspring helps to make each offspring a good competitor. Species with populations that tend to stay near

carrying capacity are called **K-selected** species because the letter K is the variable used for carrying capacity (see Chapter 12). Many endangered species are K-selected. Their slow reproduction can make it difficult for the species to recover from low numbers. Often K-selected species have large bodies, requiring large areas of habitat per individual. Habitat is often limited. Both r- and K-selection strategies are life history strategies. They are driven by individual selection, but result in characteristic population dynamics.

The durian tree (Figure 16) is a good example of a K-selected plant. It can grow 50 m tall and produces relatively few, large fruits (weighing up to 3 kg), each of which contains few very large seeds. Durian trees may live for more than 150 years. Durian trees are cultivated in tropical regions because the fruit is valuable, though reactions to the odor and taste range from delight to revulsion.

**A**

http://commons.wikimedia.org/wiki/File:Durian_Tree.jpg

**B**

https://commons.wikimedia.org/wiki/File:Durian_in_black.jpg

Figure 16. **A**. Durian tree (*Durio zibethinus*). **B**. Durian fruit cut open.

Whether a species is classified as r-selected, K-selected, or in between depends on multiple variables, including longevity, juvenile survivorship, investment per individual offspring, and fecundity (Figure 17). As a result, some species are not easily classified as r-selected or K-selected. They may have traits somewhere in the middle of the extremes, or have some traits that are considered r-selected and others that are considered K-selected.

Figure 17. Multidimensional model of r-selected and K-selected strategies. A species might be classified at different ends of the spectrum on the different components of life history strategies. The relevant axes depend on the taxonomic group of interest. Investment per offspring could be measured as the size of seeds, time spent raising offspring, or many other measures. The definition of "high" or "low" will vary depending on the taxonomic group being studied.

Dungeness crabs from the Pacific Northwest (Figure 18) are not easily categorized as r-selected or K-selected. The female can produce over 2 million eggs at a time and does not provide care after they are hatched. On the other hand, the female carries her eggs on her abdomen for months until they hatch, which is a form of parental care. She usually moves and feeds very little when she is carrying eggs, so the parental care has a high cost. It takes 2 years for the crabs to be sexually mature and they live several years. These are K-selected traits. The multiple axes of life history traits show that some of the life history traits of this species are more common in r-selected species, while others are commonly associated with K-selected species (Figure 19).

http://www.adfg.alaska.gov/index.cfm?adfg=dungenesscrab.photogallery&number=7

Figure 18. Dungeness crab (*Metacarcinus magister*) with eggs. The crab is upside-down to show the bright orange mass of eggs held in place by her abdomen.

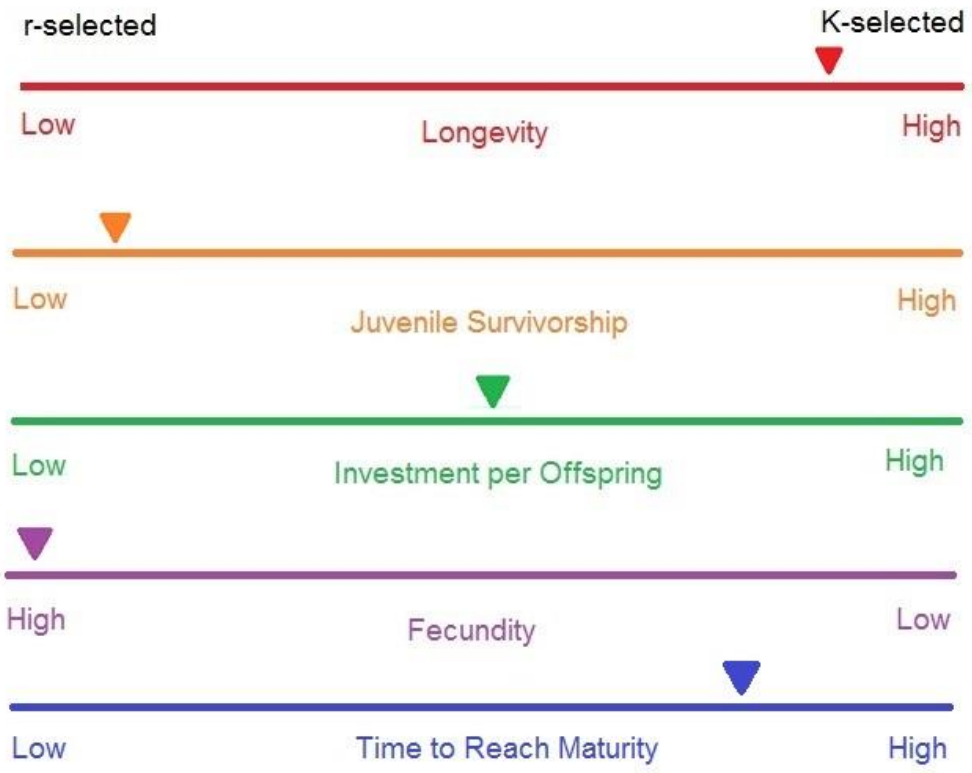



Figure 19. Classification of Dungeness crabs on multiple axes of life history strategy. The terms low or high are relative to the taxon being studied.

Weeping willow trees (Figure 20) also have a mixed life history strategy. They live for 50 years and can get very large (over 15 m). They invest in long-lasting woody roots, trunks, and branches. These are K-selected strategies. Willows grow quickly (over 3 m a year) and have relatively soft wood and extremely high seed production. These are r-selected strategies.

https://commons.wikimedia.org/wiki/File:Weeping_Willow_by_Pond.jpg

Figure 20. Weeping willow tree (*Salix* sp).

There is a trade-off between reproducing in the present and reproducing in the future. Some species reproduce only once and spend all their resources on one set of offspring, usually dying soon afterward. For example, the mouse ear cress lives less than two months and produces only one batch of seeds before dying. Sockeye Salmon spend years feeding in the ocean, storing up resources for their burst of reproduction. After they fight their way back to the freshwater stream where they hatched, they reproduce and die.

Species may also have different patterns under different environmental conditions. Some annual plants can spread out their reproduction over two or three years. An environment that causes major die-offs may cause type I curves even though the species has a type III curve in a more stable environment. Individuals in a favorable environment, or even a good year, may invest a lot more in reproduction than they would in a poor environment. Humans are a K-selected species, but because we can intentionally control reproduction, birth rates per female can vary a lot between populations. For a discussion of mortality and investment in offspring by humans, see **Make the Medical Connection: Infant Mortality and Birth Rate**.

**Make the Medical Connection: Infant Mortality and Birth Rate**

Improving the survivorship of human infants can stabilize population size. In countries with little support for elderly or disabled citizens, having children may be the only retirement and disability plan available. If children tend to die young (high infant mortality), parents must have more children so that some are still alive when they are old.

When infant mortality rates decrease in a country, women tend to have fewer children (Figure 21). This allows parents to provide more resources (such as food, education, health care) to each child. This is a life history tradeoff, shifting from more children with less investment in each to fewer children with more investment in each. In the long term, this can lead to a more stable population with fewer famines and outbreaks of disease. Providing educational opportunities to women and increasing the standard of living are also correlated with lower birth rates.

Modified from: http://www.cdc.gov/osels/scientific_edu/ss1978/lesson4/Section4.html

Figure 21. Correlation between infant mortality and total fertility rate (average number of babies born per woman) in 194 countries. Each dot represents a country.

**Analyze the Figure**

- In countries where infant mortality was about 150/1000 live births, about how many children did women have on average?
- In countries where infant mortality was about 10/1000 live births, about how many children did women have on average?
- Is there much variation in fertility rate at the same infant mortality rate? How would you explain this?

**Check your Understanding**

- What do r-selected species tend to have in common?
- Which survivorship curve (I, II, or III) describes K-selected species best?
- If an individual lives in a risky environment, is it usually better for it to produce many "cheap" offspring or few "expensive" offspring?

**Do Try this at Home: Endangered Species**

Make a hypothesis about whether the endangered species in your state are more likely to be K-selected or r-selected. Identify some of these species your state government's natural resources web sites. Then look up a few key factors on the species, such as how long they live or how many offspring they produce per year. You may also spot other life history patterns. Compare your findings to your hypothesis.

**Life History Patterns and Age Structure Influence Population Dynamics**

As discussed in Chapter 12, each species has a characteristic intrinsic rate of increase ($r_{max}$), the maximum number of offspring produced per individual under the best possible conditions. The intrinsic rate of increase limits the rate of population growth. Populations of K-selected species have lower maximum growth rates than populations of species that are r-selected because their $r_{max}$ rates are lower. This does *not* mean that the actual population growth rate (r) is always greater for r-selected species. It does mean that under optimal conditions for each species, the K-selected species will have a lower population growth.

Life history patterns are critical factors in preserving threatened species. Species that are r-selected, which have a higher $r_{max}$, can quickly recover from low population size if the environment is favorable. K-selected species—with their lower $r_{max}$— may recover very slowly or not at all. For example, most penguins only produce one or two eggs a year under the best conditions. They will not be able to produce as many offspring as fruit flies produce when conditions are optimal for them. Populations of penguins or fruit flies can increase, decrease, or remain the same, but the *maximum* potential population increase of penguins is lower than the *maximum* potential population increase in fruit flies due to intrinsic limits on penguin reproduction.

The method used to calculate the rate of population change in Chapter 12 assumes that reproductive rate for a population will remain the same. This is not always an accurate assumption for many reasons, including the environment and the ages of individuals in the population.

The offspring produced per individual may depend on the age of the individual, especially in long-lived species. Individuals may reproduce less early or late in life. Even when individuals are

sexually mature, they may lack the ability to compete for mates or successfully raise offspring. Extensive study of individual populations may be needed to understand trends and variation in reproductive output at different life stages.

Researchers studied a population of Adélie penguins (Figure 22) on Ross Island off the coast of Antarctica for several years to learn about how survivorship and breeding success changed with age. Adélie penguins have one breeding season a year and only attempt to raise 1 or 2 offspring a year. Many eggs do not hatch, and many young chicks die, so researchers used the number of fledglings (birds old enough to have adult-type feathers) to measure breeding success.

https://en.wikipedia.org/wiki/Penguin#/media/File:Antarctic_adelie_penguins_(js)_21.jpg

Figure 22. Adélie penguin (*Pygoscelis adeliae*) feeding its chick. The chick is almost adult size, but has not yet fledged—it still has mostly downy feathers.

The adults feed in the ocean, but their breeding grounds can be 100 km from the water, depending on the size of the sea ice sheet. Raising chicks requires the parents to spend long periods of time without eating and to repeatedly make a long, difficult journey from the breeding grounds to the sea as they alternate parenting duties with their mate. The entire breeding season lasts about 50 days. Ice melts as the weather warms, leaving the fledglings a much shorter journey to the sea.

Young penguins have lower reproductive success than older breeders. Adult breeders have an average success rate of 1 fledgling per pair. The average number of fledglings per 3-year-old female was only 0.3. Males did not breed until age 4, and then they only produced an average of 0.2 fledglings. Younger penguins may not have enough fat reserves or hunting skill to breed successfully even though they can produce viable eggs or sperm.

A population with a large portion of penguins under 3 years of age would have a lower potential rate of growth than one with more penguins in their peak reproductive years. When the young individuals reach their peak reproductive years, the potential rate of increase for the population will increase. Whether the potential for growth is realized will depend on extrinsic factors, such as resource levels, disease, predation, competition, and natural disasters. Age-specific reproductive output can be combined with survivorship data to refine estimates of future population growth (See **Taking it Further: Calculating Net Reproductive Rate and Generation Time**).

**Taking it Further: Calculating Net Reproductive Rate and Generation Time**

Ecologist usually track the number of females produced per female when calculating population trends for species with separate sexes. If there are equal numbers of males and females, the total number of offspring per individual would equal half the total number of females produced per female. If the sex ratio is unequal, it is important to follow the females because in mating systems where one male can fertilize several females, females will have a greater influence on population growth than males.

Researchers studying Adélie penguins in Antarctica used information on female breeding success at different ages to make a fecundity table (Table 4). Values in the third column were calculated by dividing the number of *breeding* females of a specific age by the *total* number of females that age. Multiplying the second column by the third results in the number of fledglings per female (both breeders and non-breeders). Total fledglings per female is divided by 2 for the final column because it is assumed that half the chicks are female. This number is fecundity ($m_x$, where x = age). Because penguin lifespans are longer than the length of the study, researchers extrapolated some values. For more on age-related differences in breeding, see **Testing Hypotheses: Why Do Non-Breeding Penguins Visit Breeding Grounds?**

Table 4. Fecundity table for a population of Adélie penguins on Ross Island (1967-1974). Based on Table 9.7 from Ainley, D.G, LeResche, R.E and Sladen, W.J.L. (1983). *Breeding Biology of the Adélie Penguins*. U. of California Press: Berkeley.

| Age (years) | Fledglings per Female Breeder | Proportion of Females Breeding | Fledglings per Female (all) | Female Fledglings per Female (all) $m_x$ |
|---|---|---|---|---|
| Younger than 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 |
| 3 | 0.3 | 0.17 | 0.051 | 0.026 |
| 4 | 0.4 | 0.49 | 0.196 | 0.098 |
| 5 | 0.6* | 0.68 | 0.408 | 0.204 |
| 6 | 0.9 | 0.82 | 0.738 | 0.369 |
| 7 and older | 1 | 0.9 | 0.9 | 0.45 |

*value corrected from source table

**Continued**

**Taking it Further: Calculating Net Reproductive Rate and Generation Time, cont.**

Data on survivorship and fecundity can be used to create a table that estimates the reproductive potential of a population (Table 5). The proportion of females surviving to the start of an age category is $l_x$. The number of female fledglings per female ($m_x$) is taken from the final column of Table 4. The fourth column is the product of $l_x$ and $m_x$. The final column is the result of multiplying the first column (x) and the fourth column ($l_x m_x$).

Table 5. Survivorship and fecundity for Adélie Penguins on Ross Island, 1961-1969. The value for $m_x$ is from a slightly different timeframe. Based on data from Ainley, D.G, LeResche, R.E and Sladen, W.J.L. (1983). *Breeding Biology of the Adélie Penguins*. U. of California Press: Berkeley.

| Cohort (X) | $l_x$ | $m_x$ | $l_x m_x$ | $x l_x m_x$ |
|---|---|---|---|---|
| 0 | 1 | 0 | 0 | 0 |
| 1 | 0.513 | 0 | 0 | 0 |
| 2 | 0.263 | 0 | 0 | 0 |
| 3 | 0.235 | 0.026 | 0.006 | 0.018 |
| 4 | 0.21 | 0.098 | 0.021 | 0.082 |
| 5 | 0.188 | 0.204 | 0.038 | 0.192 |
| 6 | 0.168 | 0.369 | 0.062 | 0.372 |
| 7 | 0.15 | 0.45 | 0.068 | 0.473 |
| 8 | 0.134 | 0.45 | 0.060 | 0.482 |
| 9 | 0.12 | 0.45 | 0.054 | 0.486 |
| 10 | 0.107 | 0.45 | 0.048 | 0.482 |
| 11 | 0.096 | 0.45 | 0.043 | 0.475 |
| 12 | 0.086 | 0.45 | 0.039 | 0.464 |
| 13 | 0.077 | 0.45 | 0.035 | 0.450 |
| 14 | 0.069 | 0.45 | 0.031 | 0.435 |
| 15 | 0.061 | 0.45 | 0.027 | 0.412 |
| 16 | 0.055 | 0.45 | 0.025 | 0.396 |
| 17 | 0.049 | 0.45 | 0.022 | 0.375 |
| 18 | 0.044 | 0.45 | 0.020 | 0.356 |
| 19 | 0.039 | 0.45 | 0.018 | 0.333 |
| | | **Sum** | **0.616** | **3.142** |

The sum of the fourth column is the net reproductive rate, $R_o$. This number (0.616) indicates the average number of females each female in the current population will produce in the next round of breeding. For penguins that will be next year. A population with a reproductive output of 1 will not increase or decrease. Each female is producing—on average—one replacement for herself. If $R_o$ is greater than 1, the population is increasing. Because $R_o$ is less than 1 for the Ross Island Adélie penguins in this study, we can conclude that the population was declining. In periods when the environment was more favorable, we would expect to see higher values for survival and reproduction. Obviously, if $R_o$ is consistently below 0, the population will disappear. If the age distribution remains stable, $R_o$ is also the average number of females that any female will produce in her lifetime.

**Continued**

**Taking it Further: Calculating Net Reproductive Rate and Generation Time, cont.**

Multiplying $R_o$ by the number of newly hatched females will estimate the number of females in the next *generation* (not the next breeding cycle). The average generation time (G) is a measure of the average time between when a female is produced (hatched, in this case) and when she produces her offspring. It is also an estimate of the time it will take for the population to increase by $R_o$. It assumes that all the reproduction happens at one age. This is true for some species, but many species reproduce multiple times. For these species, G produces a value that is weighted by the number of offspring produced at each age. The average generation time is calculated by taking the sum of the values in the final column and dividing by $R_o$. In this case, 3.142/0.616 = 5.1. This means that the generation time for female penguins was about 5 years. In other words, the average time from a female hatching to a female raising her own offspring is about five years.

**Testing Hypotheses: Why Do Non-Breeding Penguins Visit Breeding Grounds?**

Male Adélie penguins leave the foraging area and arrive on the breeding grounds first to establish small territories that will be their nest sites. The earliest males get the best sites. Older breeders arrive first, then the younger breeders arrive. Non-breeding penguins also start to travel to the breeding grounds when they are 2 or 3 years old. Some individuals visited the breeding grounds 4 years in a row before breeding. The large investment of time and energy to visit the site indicates that there is some benefit to being at the breeding area even for individuals that did not breed yet.

Researchers gathered data that could be used to evaluate potential hypotheses to explain why non-breeders would travel to the breeding site when they were not yet ready to breed:

> Hypothesis 1: The non-breeders learn skills (such as courtship or raising young) that will increase their success in later years.
>
> Hypothesis 2: The non-breeders improve their access to better nest sites in later years by gathering information on the area and occupying sites.
>
> Hypothesis 3: The non-breeders form social bonds with opposite-sex partners, increasing their likelihood of mating with that individual in future years.

The non-breeders spent a lot of time wandering around the breeding area. Some sat on empty nests by themselves. Some formed pairs and built nests, but did not breed. The proportion of time spent on these behaviors changed with time and experience. For example, wandering behavior (without sitting alone on a nest, pairing, or breeding) was more common in young non-breeders and in non-breeders making their first visits to the breeding site (Table 6).

Table 6. Percent of non-breeding Adélie penguins that spent time wandering in the breeding area, categorized by the age of the penguin and how many visits it had made to the breeding area. Based on Table 9.7 from Ainley, D.G, LeResche, R.E and Sladen, W.J.L. (1983). *Breeding Biology of the Adélie Penguins*. U. of California Press: Berkeley.

| Age (years) | Visit to the Breeding Area | | | | |
|---|---|---|---|---|---|
| | 1st | 2nd | 3rd | 4th | 5th |
| **2** | 73 | | | | |
| **3** | 52 | 43 | | | |
| **4** | 33 | 24 | 23 | | |
| **5** | 21 | 17 | 15 | 14 | |
| **6** | 14 | 14 | 6 | 2 | 0 |
| **7** | 0 | 0 | 0 | 10 | 0 |

**Analyze the Table**

- What percentage of non-breeding 2-year-old penguins spent time wandering?
- Which non-breeding penguins were more likely to wander, 5-year-old penguins on their first visit or 4-year-old penguins on their second visit?
- Why would there be few 7-year-old penguins that are non-breeders?

Other behaviors became more common with age and experience. Establishing a territory became more common. The wandering behavior of young and inexperienced birds was mostly around the site where they had hatched. Eventually, the birds concentrated their wandering near a site that would usually become their breeding territory in future years. Adélie penguins make simple nests of small stones. As they gained age and experience, their nests improved from simple scooped-out spots to well-formed rings of stones.

Forming pairs (though still not breeding) was rare in younger birds and new arrivals (Table 7). As the birds gained 2 or 3 more years of experience, they became more likely to form pairs, but after that, the patterns were less consistent.

Table 7. Percent of pair formation in non-breeding Adélie penguins, categorized by the age of the penguin and how many visits it had made to the breeding area. Based on Table 9.7 from Ainley, D.G, LeResche, R.E and Sladen, W.J.L. (1983). *Breeding Biology of the Adélie Penguins*. U. of California Press: Berkeley.

| Age (years) | Visit to the Breeding Area | | | | | Total # of Non-Breeding Penguins in Category |
|---|---|---|---|---|---|---|
| | 1st | 2nd | 3rd | 4th | 5th | |
| **2** | 11 | | | | | 791, 0, 0, 0, 0 |
| **3** | 20 | 25 | | | | 1508, 273, 0, 0, 0 |
| **4** | 22 | 25 | 20 | | | 437, 527, 80, 0, 0 |
| **5** | 24 | 24 | 24 | 28 | | 98, 193, 147, 36, 0 |
| **6** | 38 | 16 | 20 | 24 | 40 | 21, 51, 49, 41, 5 |
| **7** | 33 | 0 | 14 | 30 | 50 | 3, 6, 7, 10, 2 |

**Analyze the Table**

- Which non-breeding penguins were more likely to form pairs, 7-year-old penguins on their first visit or 2-year-old penguins on their first visit?
- Why might 2-year-old penguins be unlikely to form pair bonds?
- Were penguins over 3 years old more likely to form pair bonds if they had visited the breeding grounds before? Support your answer with specific data. Note any inconsistencies in the data.

One study followed non-breeding pairs of individually marked penguins to determine whether the non-breeding pairs would become breeding pairs the following year. In 14 cases, both individuals returned the following year. Twelve of the pairs formed by non-breeders the previous year became breeding pairs.

**Evaluate the Hypotheses**

- Which hypotheses are supported by the data gathered in the study?
- It is possible for data to support multiple hypotheses.
- Could any of the hypotheses be refuted based on the data?

**Check Your Understanding**

- Why might reproductive output vary with age, especially in long-lived species?
- Why is it important to understand age-specific reproduction patterns in species?

# Key Concepts

- R-selected species maximize reproductive rate. They produce many offspring and invest very little in each one. They tend to have population sizes that vary a lot.
- K-selected species maximize competitive ability of their offspring. They produce few offspring and invest a lot in each one. They tend to have population sizes that are relatively stable.
- Reproductive output varies by age in long-lived species.
- Information on population age structure, mortality and reproduction can be used to predict changes in population size.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately describe and explain different patterns of survivorship*
2. *Correctly identify relationships between survivorship, reproductive investment, and environmental factors*
3. *Make reasonable predictions of future population trends based on population structure and fecundity patterns*
4. *Compare life history patterns between species, making valid inferences about differences and similarities*

1. Refer to the data for black-capped chickadees (Table 8).

Table 8. Chickadee survivorship data.

| Age (x) | Number of Survivors |
|---|---|
| 0 | 106 |
| 1 | 28 |
| 2 | 10 |
| 3 | 4 |
| 4 | 2 |
| 5 | 0 |

*A.* Make a line graph of this data set in the incomplete graph below (Figure 23). *(Model Skill—Making Line Graphs)*

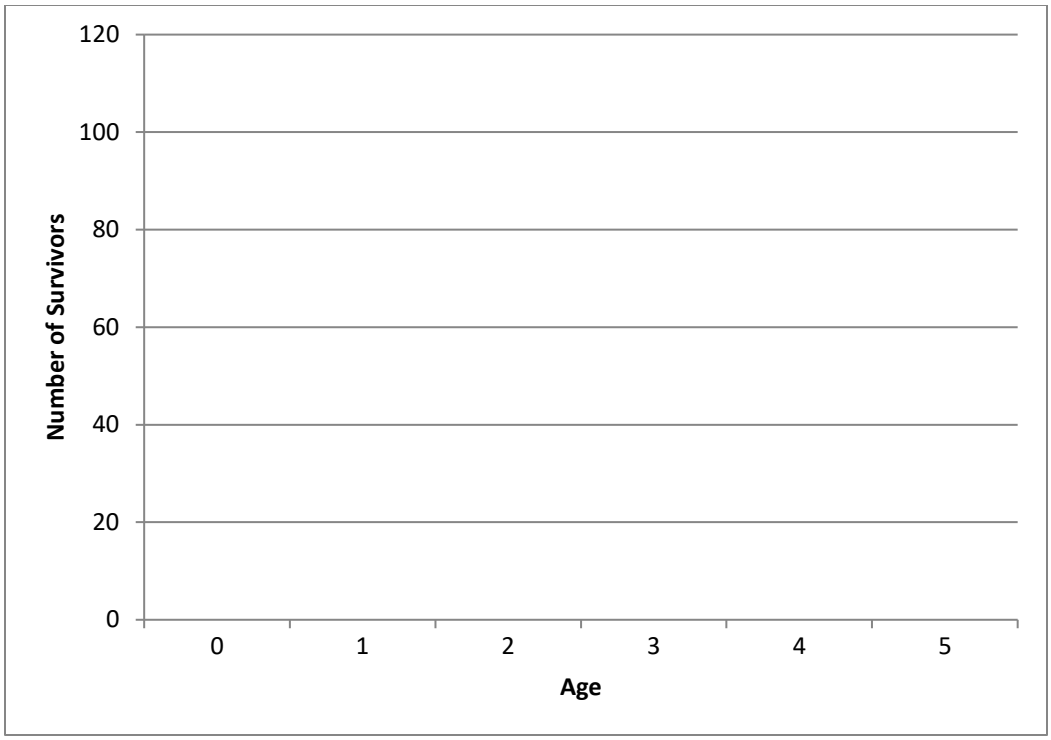
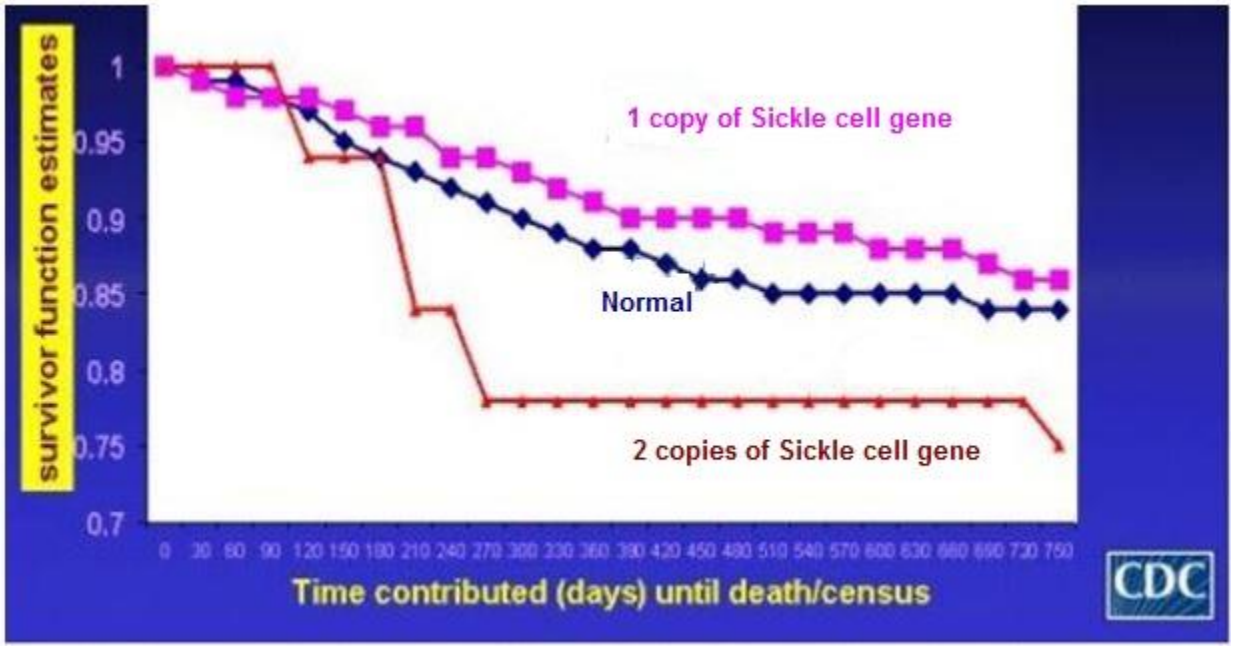



Figure 23. Incomplete survivorship curve.

B. Describe this pattern in words. *(Learning Outcome 1)*
C. Chickadees stay in cold climates all year. Severe storms can kill them. How would this help to explain their survivorship pattern? *(Learning Outcome 2)*

2. Refer to Figure 24.




Modified from: http://www.cdc.gov/malaria/about/biology/sickle_cell.html.

Figure 24. Human survivorship curves for children in western Kenya. Sickle cell disease is a serious genetic condition. Malaria is a major source of mortality in this region. Researchers were testing the hypothesis that having one copy of the sickle cell gene provides some protection against malaria.

A. Describe the general patterns in survivorship for each curve. *(Learning Outcome 1)*
B. Do children in western Kenya benefit from having the sickle cell trait (one copy of the Sickle cell gene)? Explain your answer. *(Learning Outcome 1)*
*C.* Would you expect to see similar patterns in the US among children of African ancestry? Explain your answer. *(Learning Outcomes 1 & 2)*

3. Refer to Figure 25.

Figure 25. Survivorship curve for red squirrels (*Tamiasciurus hudsonicus*). Based on data from: Halvorson, C.H. and Engeman, R.M. (1983). Survival analysis from a red squirrel population. *Journal of Mammalogy* 64: 332-336. Photo: http://en.wikipedia.org/wiki/American_red_squirrel#/media/File:Tamiasciurus_hudsonicus_CT.jpg.

A. Does this curve best fit type I, II, or III? Explain your answer, discussing maximum life span and rate of mortality.
B. What is the approximate probability that a red squirrel will reach 45 months?
C. What environmental factors might cause a change in survivorship patterns? Explain your reasoning.
D. Would you predict that red squirrels are r-selected, K-selected, or intermediate between the two extremes? Explain your reasoning.
*(Learning Outcomes 1, 2 and 4)*

4. **Take it Further:** Researchers studying beavers in Kansas collected information on the age structure and fecundity of the population using carcasses turned in by fur trappers. The data are summarized in Table 9.

Table 9. Fecundity table for beavers (*Castor canadensis*) in Kansas, 1988-1991. Age is reported in years. Two extra columns are provided for calculation. Based on: Welch, D. K., Robel, R. J., & Fox, L. B.. (1993). Age Structure and Reproductive Activity in a Kansas Beaver population. *Transactions of the Kansas Academy of Science*, *96*(3/4), 186–195.

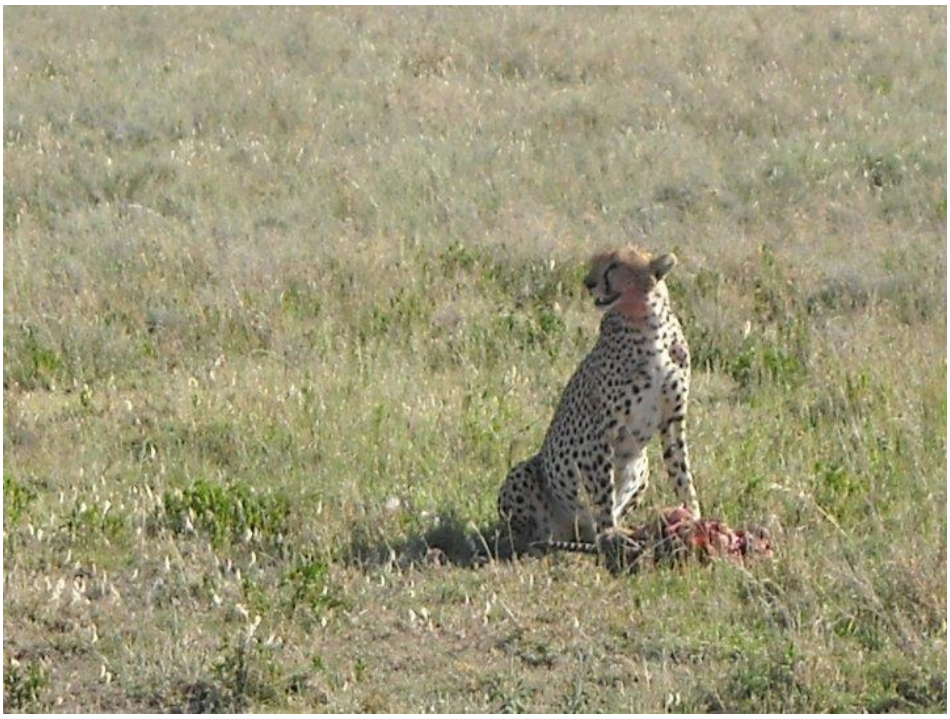
| **Age (x)** | **$n_x$** | **$l_x$** | **$m_x$** | | |
|---|---|---|---|---|---|
| 1 | 70 | 1.000 | 0 | | |
| 2 | 34 | 0.486 | 2 | | |
| 3 | 30 | 0.429 | 3.8 | | |
| 4 | 13 | 0.186 | 4.3 | | |
| 5 | 22 | 0.314 | 4.4 | | |
| 6 | 10 | 0.143 | 5 | | |
| 7 | 10 | 0.143 | 4 | | |
| 8 | 4 | 0.057 | 4 | | |
| 9 | 2 | 0.029 | 4 | | |
| 10 | 1 | 0.014 | 4 | | |
| 11 | 2 | 0.029 | 4 | | |
| 12 | 2 | 0.029 | 4 | | |

A. Calculate the reproductive output ($R_o$) for this population (hint: see Table 5). Is this population likely to be increasing or decreasing?
B. The fecundity numbers were determined by looking at embryos or scars of recent embryos/fetuses in female reproductive tracts. Is this likely to be an overestimate or underestimate of actual fecundity? Explain your reasoning.
C. Is this a static or a dynamic life table? Explain your reasoning.
D. How would you compute generation time (G)?

*(Learning Outcome 3)*

# Unit V

# Communities



Burton 2009

A cheetah with its kill in Serengeti N.P., Tanzania.

**Interactions between members of communities shape each other's ecology and evolution**

**Unit Outcomes**

- Accurately categorize interactions between species as predation, parasitism, commensalism, mutualism, or competition, using valid evidence
- Clearly articulate the influence of interspecific interactions on the species involved
- Accurately explain how disturbances influence ecological communities
- Articulate reasonable explanations for patterns of biodiversity and clearly explain the consequences of this diversity
- Effectively apply concepts of natural selection to community dynamics

**Unit V: Communities**

# Chapter 14: Winners and Losers: Predation and Parasitism

### Case Study Part 1: The Plague of Guinea Worm

https://commons.wikimedia.org/wiki/File:Preventing_Guinea_worm_disease_in_Chad_%2834173755220%29.jpg

Figure 1. Children in Chad holding water filters that protect them from guinea worm. The treatment for this parasite has not changed for thousands of years, but understanding the worm's life cycle has nearly irradicated it.

Imagine that your only source of drinking water is infested with a parasite. This parasite will not make itself known for about a year. Then you will feel burning pain down your leg and develop a painful, itchy blister, probably around your foot or ankle. Eventually, the end of a worm will pop out of the blister. It may emerge as you bathe your foot in water to make it feel better. This is a guinea worm. The only treatment for it is to wind the worm slowly around a stick over several weeks. The worm could be a meter long. If you get impatient and try to remove it too quickly, you risk breaking it, which can increase the chance of infection. You may have a fever, nausea, vomiting, and other symptoms. You will probably be in pain and have trouble walking even after

the worm is gone. If you are still drinking the contaminated water, it is just a matter of time before the next worm breaks out.

In 1986, this was reality for people in 20 African nations. At least 3.5 million people were infected by guinea worm that year. Health workers had no cure to offer other than the age-old process of winding the worm around a stick. They were only able to treat the wound itself. People with guinea worm disease—also called dracunculiasis—suffer and may be unable to work, but they usually survive unless they get a bad infection or other complications. The female worm needs its host alive so that it will be carried back to the water to release her offspring. Then the cycle of infection begins for another year.

Public health officials knew that a clean water supply would help fight many diseases, but there were usually limited resources and equipment for digging enough wells or treating the water effectively. The only way to defeat the parasite was to understand its life cycle and find a way to disrupt it.

**Learning from the Case Study**

- How do people get infected with guinea worm?
- Why was infection so common?
- What information might be useful in fighting a parasite like guinea worm?

# Learning Outcomes

1. *Accurately analyze relationships between species in a community*
2. *Make reasonable predictions about the influences of exploitation on populations on each other*
3. *Draw reasonable conclusions about evolution and exploitative interactions*

**Vocabulary Toolkit**

**Word Watch List**

**Niche**: Organism's role in the community, including its habitat requirements and interactions
**Fundamental niche**: The niche that potentially meets an organism's needs
**Realized niche**: The part of the niche that is available to an organism. Species interactions may make the realized niche smaller than the fundamental niche
**Predation**: Exploitation interaction between species in which one animal dies
**Parasitism**: Exploitation interaction between species in which death is rare or not required
**Commensalism**: Interaction between species in which one individual benefits and the other is neither hurt nor helped measurably
**Competition**: Interaction in which individuals attempt to use the same resources
**Mutualism**: Interaction between species in which both individuals benefit
**Pathogen**: Disease-causing organism or virus
**Vector**: Intermediate host for a parasite
**Coevolution**: Long term evolutionary interactions between two species. Changes in one species drive changes in the other, leading to a series of changes in both species
**Keystone species**: Species that are small in number but have a significant influence on a community
**Trophic cascade**: Ecosystem-wide changes caused by top predators

### Each Species has a Niche in an Ecological Community

Recall that an ecological community consists of all the species in a given place. These species can interact in many ways, directly and indirectly. The "place" of a species in a community is known as its **niche**. The niche refers to both the habitat needs of a species and its interactions with other species. For a terrestrial plant, describing a niche may include climate, soil type, pollinators, seed dispersers, herbivores that eat it, microbes that cause diseases, and bacteria and fungi that allow it to absorb nutrients.

Interactions between members of different species are usually characterized by whether individuals of each species are harmed or benefitted by the interaction (Table 1). Harm could include death, damage, or loss of resources. Benefits are usually gains of resources or reproductive opportunities.

Table 1. Description of community interactions. Beneficial effects from the interaction are marked with a +. Harmful effects are marked with a --. If there is little or no harm or benefit, it is marked with a 0.

| Interaction | Effect on Members of Species 1 (term for species) | Effect on Members of Species 2 (term for species) |
|---|---|---|
| **Predation** | + (Predator) | -- (Prey) |
| **Parasitism** | + (Parasite) | -- (Host/Vector) |
| **Commensalism** | + (Commensal) | 0 (Commensal) |
| **Competition** | -- (Competitor) | -- (Competitor) |
| **Mutualism** | + (Mutualist) | + (Mutualist) |

A species that is the prey in one interaction might be the predator in another interaction. Any individual may have many interactions with different species that could make it a competitor, host, parasite, mutualist, or commensal as well.

**Misconception Alert: All species depend on each other**

**FALSE.** Some species harm other species through exploitation or competition. The kernel of truth in this misconception is that the result of adding or losing a species is often unpredictable. If we could eradicate parasites like tapeworms, the community might be changed in ways that could cause other problems. This uncertainty is unlikely to stop the fight to destroy pathogens that cause human suffering.

The part of a niche that is determined by the needs and tolerances of a species is called the **fundamental niche**. Most ecologists focus on abiotic factors and food resources to define the fundamental niche. The entire fundamental niche may not be available to an organism if superior competitors are using it. The species that is outcompeted will be restricted to a portion of the fundamental niche, the **realized niche**. Some ecologists would include other interactions, such as parasitism or predation as factors that would cause a realized niche to be smaller than a fundamental niche.

**Check Your Understanding**

- What is an ecological niche?
- Could two species living in the same area have identical niches?
- Why is it important to think about costs and benefits in terms of individuals, rather than species?

**Predators Kill Prey**

In predation, predators kill individuals of the prey species. When an amoeba engulfs a bacterium, a wolf pack kills a moose, or a squirrel eats an acorn, this is predation. In parasitism, the parasite takes something from the host. If death occurs, it is only incidental. Parasitism will be explored later in this chapter. Competition, commensalism, and mutualism will be discussed in Chapter 15.

Countless strategies for getting prey have evolved (Figure 2). Tiny barnacles and enormous blue whales filter prey out of the water. Wolf spiders and falcons attack prey from above. Venus fly traps and trapdoor spiders capture insects. Angler fish and black egrets lure fish into catching range. Predators may sit and wait for their prey or run them down. They may use specialized weapons or chemicals. They may hunt alone or in groups.

It may have surprised you to learn that seed eating is a form predation but remember that a seed is an individual of that plant. Plants have evolved to either protect their seeds well or have so many that losses to seed predators can be tolerated. Some seeds are protected by shells, cones, spikes, or other barriers. Others are poisonous. Others are so tiny and numerous that some will probably escape detection. If seeds are far from a parent plant, there may be few seed predators (and less competition) so some seeds travel by wind, water, or animal.

**A**

https://commons.wikimedia.org/wiki/File:Tunicate_komodo.jpg

Tunicates filter small organisms from the water.

**B**

https://upload.wikimedia.org/wikipedia/commons/0/09/Kestrel_with_prey.jpg

Kestrel with its prey.

**C**

https://en.wikipedia.org/wiki/Venus_flytrap#/media/File:Dionaea_Paria_beetle.jpg

Venus flytrap with its beetle prey.

**D**

https://en.wikipedia.org/wiki/Chameleon#/media/File:Chameleon-Stage_03.jpg

Chameleon striking with its sticky tongue.

**E**

http://oceanexplorer.noaa.gov/explorations/04deepscope/background/deeplight/media/fig3c.html

Angler fish showing a structure on its head that is to lure fish near its mouth.

**F**

https://en.m.wikipedia.org/wiki/File:Sydney-brown-trapdoor-spider_002.jpg

Trapdoor spider waiting in its trap.

Figure 2. Examples of some of the many predation strategies.

Prey have a variety of traits for avoiding being eaten (Figure 3). Some hide by matching their background, staying in shelters, or being disguised. Some prey defend themselves with physical or chemical weapons. Toxic species often have showy colors or structures to advertise their ability to defend themselves (see **Evolutionary Perspective: Kin Selection and Warning Coloration**). Some harmless animals mimic dangerous animals. Octopus and squid can change their behavior, color, and shape dramatically to hide or mimic different species. Prey may use speed or agility to survive a chase. Some prey can't hide effectively. For example, large grazers are easy to see in grasslands and fish are easy to see in the open ocean. These species may "hide" in large groups. Groups of prey can also work together to defeat predators.

Avoiding predation adds another dimension to the costs and benefits of prey behavior and physiology. For example, if an area has good resources, but has little protection from predators, prey individuals may use it only when danger from predation is low. To do your own experiments on this, see **Do Try this at Home: The Landscape of Fear**. Plants may adjust their investment in protective chemicals based on whether they are being attacked by parasites such as herbivorous animals.

**Do Try this at Home: The Landscape of Fear**

The reintroduction of wolves into Yellowstone National Park has changed how prey animals such as elk forage for food. This has changed the vegetation of Yellowstone. Even when predators are not chasing prey, the prey's behavior is influenced by predators. Some ecologists call this the "landscape of fear." You can explore this idea using bird feeders. Find or make two identical bird feeders. Put the same amount of seed into each one and record the weight of the seed. Then hang the feeders in areas with high or low predation risk. For example, near the safety of trees or in the open. You might test the effect of artificial owls or the recorded call of a predator (look for one online). After the testing period, weigh the amount of seed left in each feeder.

**A**

http://eol.org/data_objects/1995845

Walking stick insects match their background.

**B**

http://commons.wikimedia.org/wiki/File:Striped_pyjama_squid.jpg

Striped pyjama squids are brightly colored, but still match their background.

**C**

http://eol.org/pages/2682739/overview

The monarch butterfly (*Danaus plexippus*) is toxic and signals its identity.

**D**

http://eol.org/data_objects/25762835

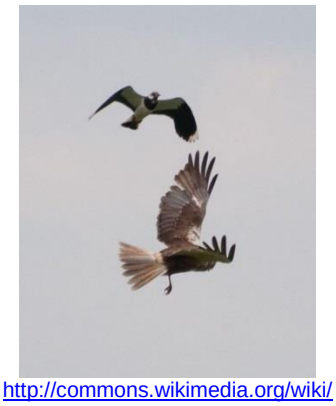
The viceroy (*Limenitis* archippus) is also toxic. It mimics the color and pattern of the monarch.

**E**

http://en.wikipedia.org/wiki/File:Moofushi_Kandu_fish.jpg

Fish stay together to avoid predation.

**F**



http://commons.wikimedia.org/wiki/File:Vanellus_vanellus_mobbing_Circus_aeruginosus.jpg

Smaller northern lapwing helps mob a larger predatory marsh harrier. Groups of prey can overwhelm a larger predator.

Figure 3. Some of the many strategies for avoiding predation.

**Evolutionary Perspective: Kin Selection and Warning Coloration**

Monarch butterflies (Figure 3C) are toxic because they eat toxic milkweed. They advertise their chemical defense with bright "warning coloration" that is easy to recognize. If a bird eats a monarch, it gets sick and avoids butterflies that look like monarchs. Advertising the fact that you are going to make your predator sick is effective evolutionary strategy, but it can be difficult to imagine how it evolved. Once the individual monarch is eaten, how does it benefit from training an individual bird not to eat it?

Assume that the ancestor of the monarch ate milkweed and was cryptic (difficult to see and recognize). It would get no benefit from being toxic. An individual that was more visible and recognizable due to a mutation would actually be more likely to be eaten. But if the bright, toxic individual lived to reproduce, it could pass that gene to its offspring. A bird that ate a bright, toxic monarch would avoid all of the brightly-colored relatives of the butterfly that it ate. Each of the dead butterfly's siblings (brothers or sisters) or offspring has a 50% chance of having the same gene that made the dead butterfly colorful. Colorful relatives will be less likely to be eaten than cryptic individuals, so the gene is likely to spread through the population. This is an example of **kin selection**, in which the relatives of an individual benefit, so the individual's genes become more common (see Chapter 11).

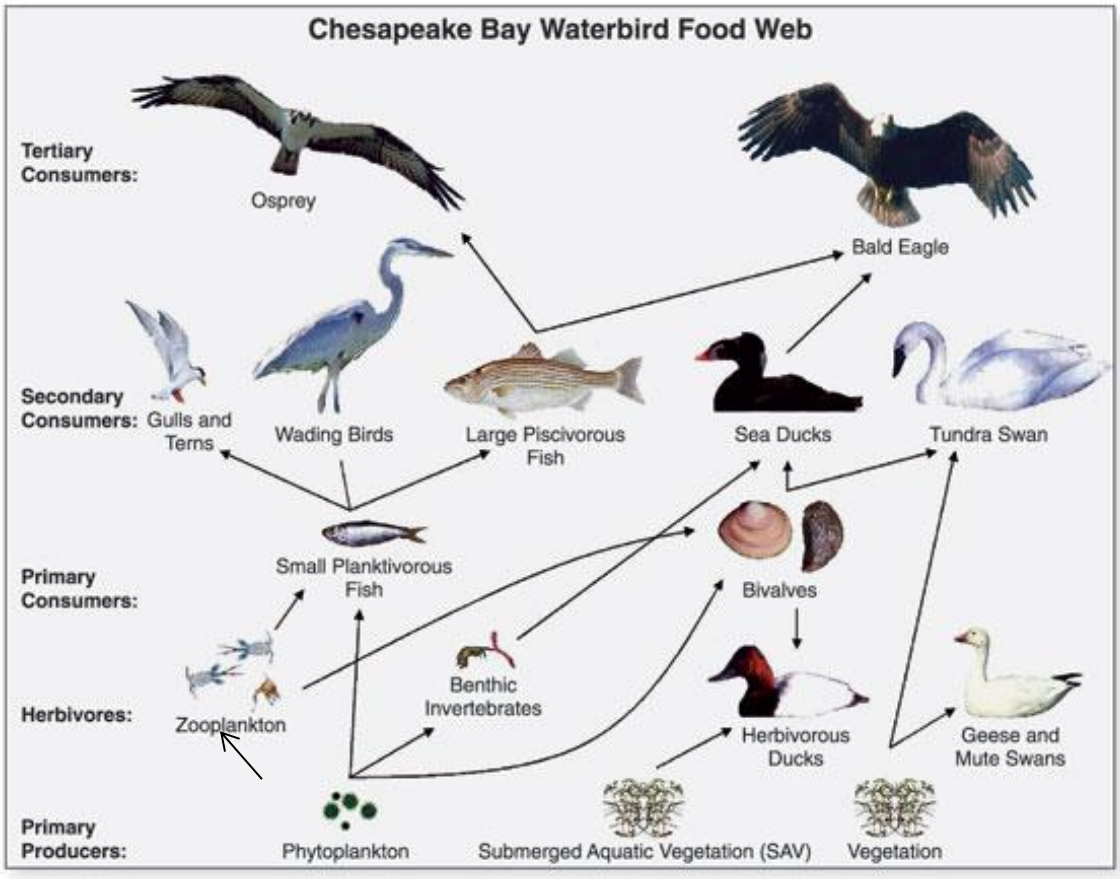
The viceroy butterfly (Figure 3D) is toxic due to eating members of the willow family. When the viceroy lives in the same range as the monarch, the two species look similar. Scientists used to think that the viceroys were a harmless species parasitizing the warning coloration of the monarchs. Now that viceroys are known to be toxic, scientists assume that both species benefit from a bird being trained to avoid the same pattern of warning coloration.

**Make a Prediction:**

- Is warning coloration more likely to evolve in species that are r-selected or K-selected? Explain your answer.
- Is warning coloration more beneficial if kin stay together in large groups, or if individuals tend to stay by themselves? Explain your answer.

**Food Webs Describe Some Community Interactions**

Food webs are models that show consumption of species (Figure 4). Food webs tend to be simplified due to the complexity of actual community interactions. Arrows usually go from organism being consumed to the organism consuming it. Producers are usually shown at the bottom of the web because they are the lowest trophic level (as discussed in Chapter 5). In the Chesapeake Bay, phytoplankton and vegetation are the producers. Through photosynthesis and other reactions, they use energy from the sun and raw materials such as nutrients, $CO_2$, and water to make their tissues. These tissues are used as food by primary consumers or herbivores. The primary consumers are eaten by secondary consumers, which are eaten by tertiary consumers. Recall from Chapter 5 that most of the energy on each trophic level is lost as heat, so there will usually be many fewer individuals on any level than on the level below it. Decomposers are often not shown on food webs because they may feed on dead organisms from any level. They are very important to communities because they break down tissues for recycling.




https://pubs.usgs.gov/circ/circ1316/html/circ1316chap14.html

Figure 4. Food web showing interactions in the Chesapeake Bay community. "Planktivorous" means plankton-eating. "Piscivorous" means fish-eating.

**Analyze the Figure**

- Which species would be classified as secondary consumers?
- If bivalves were not available, how might that influence some of the other species? Be specific about how numbers of that species would change and explain your reasoning.
- Would there be more total biomass of small planktivorous fish or large piscivorous fish? Explain your reasoning.

Food webs also allow ecologists to analyze other community interactions. They show competition for the same food resources. If a predator eats multiple prey, they may switch to the most abundant prey, competing with other species that share some of the same prey. Food webs help ecologists to predict how communities might change if species numbers change, species go locally extinct, or invasive species are added to communities.

Some food webs show other community interactions such as parasitism, mutualism, commensalism, and competition for resources other than food. As models get more complex, computers can be useful in analyzing them.

**Check Your Understanding**

- What is the difference between parasitism and predation?
- Describe some ways that individuals avoid predation.
- Why are there so few large carnivores?

**Parasites take Resources from Hosts**

When a fungus grows on an apple tree, a tapeworm lives in an animal's intestine, a vine grows on a tree, or a bison eats leaves of grass, this is parasitism. Disease-causing organisms such as bacteria are types of parasites. Parasites and viruses can be classified as **pathogens**. Viruses are similar to parasites; they invade cells and turn them into virus-producing organisms, but they are not living organisms. Unlike predation, parasitism does not require the death of the host. Often, the parasite benefits if it keeps its host alive. For example, a tapeworm will die if its host dies. The longer a sick person spreads their pathogens to others, the more the pathogen benefits.

Parasites have many types of strategies (Figure 5). They may live on the outside of their hosts and steal fluids. Familiar external parasites (ectoparasites) that attack humans include ticks, mosquitoes, and leeches. Plants have external parasites as well, such as vines that climb stems or trunks and intercept sunlight. Some parasites live within their hosts (endoparasites). Species may suffer from tapeworms, roundworms, and microscopic parasites. These parasites usually take fluids (such as blood, sap, and partially digested food) from their hosts.

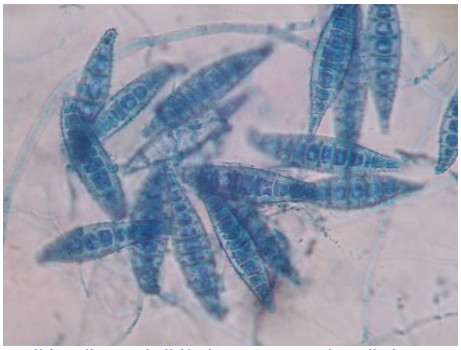
Some species—including many wasps—paralyze the larvae of other animals and lay their own eggs in the larvae. The parasitic larvae gain a habitat and a food source as they hatch and eat their hosts. Because the hosts are eventually killed, this is similar to predation, but the host has to live for a while or the exploiter will die. These exploiters are called parasitoids. There are other types of parasitism as well. Individuals of one species may steal food or other resources from individuals of another species without living in or on them. Individuals of some species trick individuals of other species into caring for them or their young.

**A**

https://commons.wikimedia.org/w/index.php?curid=30119814

Some Isopods eat a fish's tongue and take its place in the host's mouth.

**B**



https://en.wikipedia.org/wiki/Microsporum#/media/File:Macroconidia_Microsporum_canis.JPG

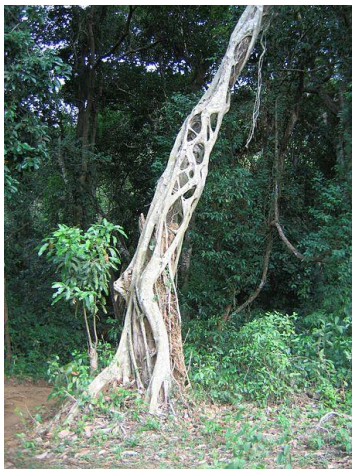
*Microsporum*, one of the fungal species that causes "ringworm" and other skin diseases.

**C**

https://en.wikipedia.org/wiki/Brood_parasite#/media/File:Reed_warbler_cuckoo.jpg

Reed warbler parent feeding much larger cuckoo, a nest parasite.

**D**

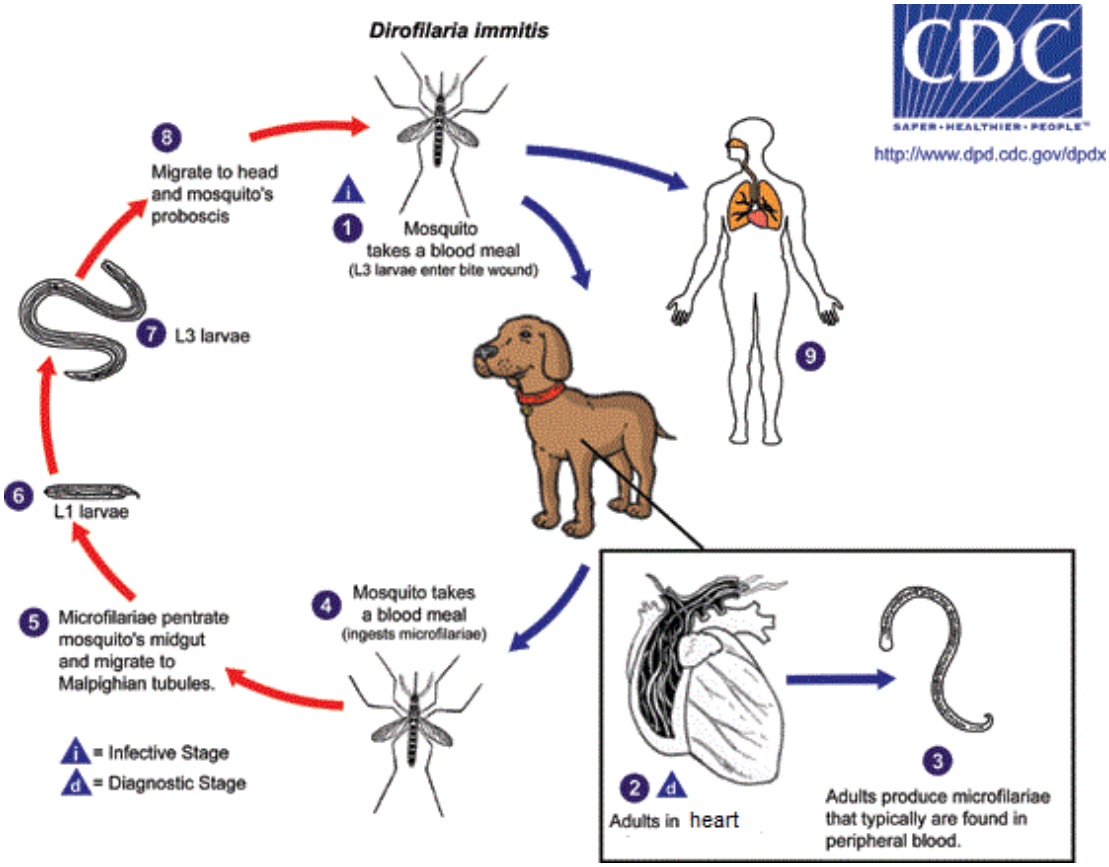


https://commons.wikimedia.org/wiki/File:Strangler_tree.jpg

Strangler fig trees climb other tree species, parasitizing the structure the host has built to reach the light.

Figure 5. Parasites use resources from their hosts in many ways.

Many parasites have more than one host. Adult heartworms live in the heart and large blood vessels of dogs and produce young worms that travel throughout the bloodstream (Figure 6). A mosquito might suck blood from the dog, taking in the juvenile worms as well. These juveniles travel into the mosquito's blood-sucking structure (proboscis) and can infect a new dog with the mosquito's next blood meal. The mosquito is a secondary host or **vector** that carries the heartworm. Many people give their dogs drugs to kill any juvenile worms that may enter their dog's bloodstream. Poisoning the adult worms in the dog's heart can kill the dog.




http://www.cdc.gov/parasites/dirofilariasis/biology_d_immitis.html

Figure 6. Life cycle of the heartworm.

Mosquitoes are vectors for heartworm, malaria, and other diseases. Health organizations often attempt to control parasites by killing vectors. A multi-host human parasite was discovered fairly recently in the United States and has become a public health threat (see **Make the Medical Connection: Lyme Disease**).

### Case Study Part 2: Conquering the Guinea Worm

Studying the guinea worm's life cycle was the key to defeating it. The larvae in the drinking water were not making people sick directly (Figure 7). When the worm larvae

emerge, they will eventually die unless they are eaten by a vector called a copepod. It is a small shrimp-like animal. People get infected with the parasite when they drink water containing the vector. This was one way the worm was vulnerable. The copepods are tiny but are much larger than the worm larvae. It is possible to filter copepods out of the water with simple methods. The larvae would be a lot more difficult to remove directly.

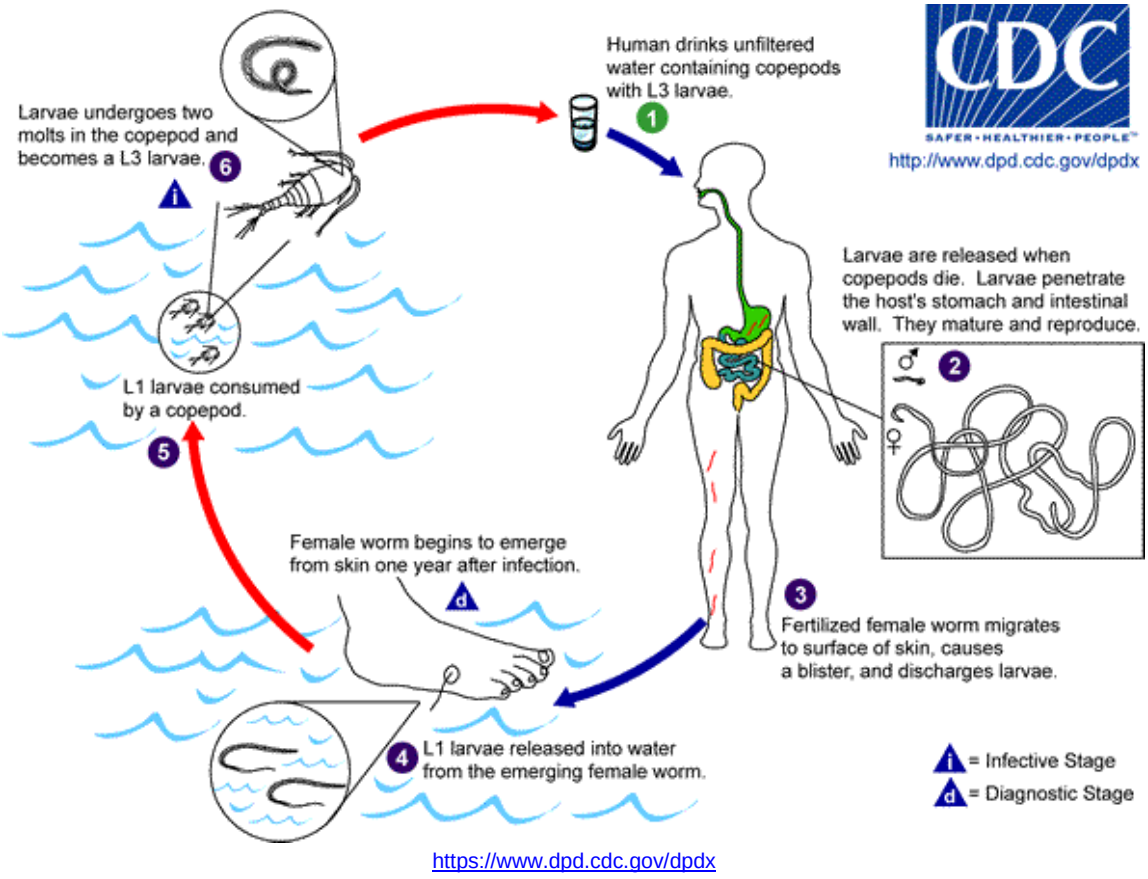



Figure 7. Life cycle of the guinea worm.

**Analyze the Figure**

- Where do the worms mature and mate?
- How do larvae get into the drinking water?
- How do larvae get into people?

One step that health officials used was to educate people about the cause of the disease. People learned that they would contaminate their drinking water if they bathed or stood in it when they had guinea worm sores. This reduced the number of larvae getting into the water. Government programs and international aid organizations also gave people low-technology water-filtering straws they could wear or carry. They taught people to use simple cloth filters on larger volumes of water. These practices prevented people from consuming infected vectors.

http://www.who.int/features/factfiles/guinea_worm/facts/en/index9.html

Figure 8. Billboard used to promote the elimination of guinea worm. The black tubes are filter straws that remove copepods from drinking water.

By 2014 there were only 126 cases of guinea worm disease in humans reported in the entire world. By 2023, there were only 14 cases (Figure 9). If the water is not contaminated for a year, the cycle is broken. Countries without the parasite now will remain free of guinea worm unless someone from an infected area introduces new larvae into it.

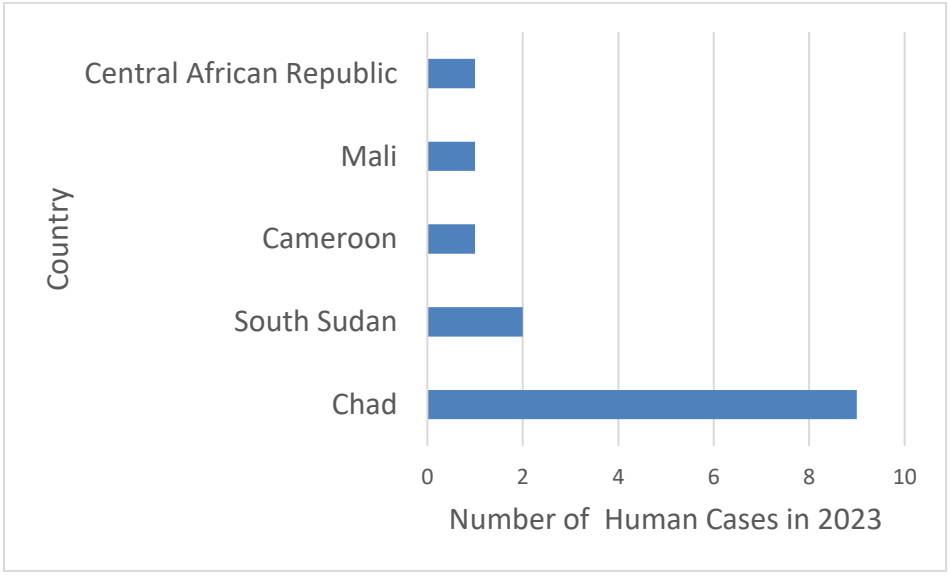



Figure 9. Number of known cases of guinea worm disease in 2023, by country.
Data from: https://www.cartercenter.org/news/pr/2024/2023-guinea-worm-worldwide-cases-announcement.html.

**Learning from the Case Study**

- How did knowledge of the parasite life cycle help in developing an effective plan for fighting it?
- What problems could potentially prevent the complete elimination of the species?
- Would you have done anything differently to combat the worm?

**Make the Medical Connection: Can parasitic worms protect us?**

https://www.niaid.nih.gov/news-events/parasiticwormsarscov2

Figure 10. Parasitic hookworm larva.

During the early years of the COVID-19 pandemic, researchers were intrigued by lower death rates and disease severity in populations that had higher levels of parasitic roundworms. To investigate the phenomenon, researchers infected mice with a roundworm that infects the lungs during part of its life cycle. Later, they infected the mice with a potentially lethal dose of a mouse version of the virus that causes COVID-19.

In the control group, only 20% of the mice survived. In the group that had recovered from the worm infection, 60% survived. The parasitic infection seems to have influenced the immune system in multiple ways. Worm-exposed mice had higher levels of CD8 T-cells, a type of white blood cell that identifies and kills body cells that are infected with viruses. When the researchers artificially reduced the level of CD8 T-cells in the worm-exposed mice, the mice were no longer protected from the virus. Macrophages are white blood cells that eat diseased cells (their name means “big eater”) and signal other white cells to the area. Mice that had recovered from the worm infection had stronger signals from their macrophages.

These findings aren’t conclusive, but they suggest that parasites can prime host immune systems to fight off other diseases.

**Check Your Understanding**

- Describe some types of parasitism.
- Why might parasites benefit from keeping their hosts alive?
- How are pathogens similar to and different from other parasites?

**Exploiters and the Exploited Often Coevolve**

As discussed in chapter 4, one species can exert selection pressure on another. Faster cheetahs are more likely to leave offspring than slow cheetahs. But faster gazelles also leave more offspring than slow ones. Parasites that can evade the immune system of their hosts leave more offspring than those that don't. Hosts with immune systems that can effectively destroy parasites leave more offspring than those with weak or easily fooled immune systems.

Throughout evolutionary history, exploiter species and victim species have shaped each other's evolution. This process is called **coevolution** to emphasize the influence the species have had on each other. In the case of exploiters and victims, this coevolution can be a sort of "arms race" that can result in extremes. For example, the rough-skinned newt (Figure 11 A) is highly toxic to almost all species, but its predator—the garter snake—has immunity to the toxin (Figure 11 B). The newts vary in how much poison they make, and the garter snakes vary in how resistant they are to the toxin. In locations with toxic newts, garter snakes with high immunity to the toxin are more successful than less-resistant snakes. But the high-resistance snakes move more slowly, probably because of the physiological traits that make them resistant, so they are at a disadvantage in areas with less-toxic newts.

**A**

https://commons.wikimedia.org/w/index.php?curid=12036399

**B**

By Wilson44691 - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=10100793

Figure 11. **A**. Toxic rough-skinned newt (*Taricha granulosa*) and **B.** toxin-resistant garter snake (*Thamnophis sirtalis*).

Adaptations generally lead to trade-offs, as seen with the toxic newts. Prey that evolve in the presence of a particular predator may be less able to escape predation by other predators, less able to resist pathogens, require more resources, or have other disadvantages. By definition, predation is lethal to *individuals* of the prey species. Do predators improve their prey *populations* by removing less-fit individuals? For more on that topic, see **Testing Hypotheses: Do Predators Target the Weak?**

**Testing Hypotheses: Do Predators Target the Weak?**

Predators are likely to be more successful at capturing weak, sick, malnourished, and less experienced prey. These individuals may be vulnerable because of some genetic defect or for non-genetic reasons, such as the environment or the ratio of predators to prey. Researchers in the American Northwest studied vulnerability to predation in juvenile steelhead (Figure 12) in the Snake River.

http://www.nwfsc.noaa.gov/news/features/steelhead_migration/index.cfm

Figure 12. Steelhead (*Oncorhynchus mykiss*).

The researchers had 3 hypotheses:

1. Predation risk depends on the condition and size of the fish and on the environment (such as water clarity and flow rate).
2. Predation risk depends on the condition of the fish alone.
3. Predation risk factors differ depending on the species of predatory bird.

They implanted over 25,000 fish with electronic identifying chips (PIT tags). When fish were captured for tagging, they were measured and classified for their overall condition based on visible damage, disease, or parasites. Researchers later searched for the tags in both live fish and the remains of fish in colonies of fish-eating birds. River conditions were also recorded. The two main predators in the study have different hunting tactics. Caspian terns (Figure 13 A) depend on surprise to catch fish when they are near the surface. Double-crested cormorants (Figure 13 B) are diving birds that chase fish underwater. Researchers used models to test the influence of the variables on fish predation by Caspian terns (Table 2).

https://en.wikipedia.org/wiki/Caspian_tern#/media/
File:Sterna-caspia-010.jpg

https://en.wikipedia.org/wiki/Double-crested_cormorant#/media/
File:Phalacrocorax-auritus-007.jpg

Figure 13. A. Caspian tern (*Hydroprogne caspia*). B. Double-crested cormorant (*Nannopterum auritum*).

Table 2. Results of statistical testing on influence of various factors on probability of steelhead predation by Caspian terns. Data from: Hostetter, N. J., Evans, A. F., Roby, D. D., & Collis, K. (2012). Susceptibility of juvenile steelhead to avian predation: the influence of individual fish characteristics and river conditions. *Transactions of the American Fisheries Society*, *141*(6), 1586-1599.

| Variable | Risk |
|---|---|
| Intermediate length (vs. Low or High) | Significant Increase |
| Low (vs. High) Steelhead Abundance | Significant Increase |
| Low (vs. High) Water Clarity | Significant Increase |
| Low (vs. High) Water Flow | Significant Increase |
| Poor (vs. Fair) Overall Condition | Significant Increase |
| Fair (vs. Good) Overall Condition | Not significant |
| Caspian Tern Abundance | Not significant |

**Analyze the Table**

- Which of the trends were statistically significant?
- What size of fish were most vulnerable to predation
- How did river conditions influence the probability of predation by Caspian terns?
- Caspian terns attack fish when they are near the surface. How might water flow and clarity influence their hunting success?

The models used to analyze predation by double-crested cormorants were slightly different. The disease portion of the condition score was used separately (Table 3).

Table 3. Results of statistical testing on influence of various factors on probability of steelhead predation by double-crested cormorants. Data from: Hostetter, N. J., Evans, A. F., Roby, D. D., & Collis, K. (2012). Susceptibility of juvenile steelhead to avian predation: the influence of individual fish characteristics and river conditions. *Transactions of the American Fisheries Society*, *141*(6), 1586-1599.

| Variable | Risk |
|---|---|
| Length | Not Significant |
| Steelhead Abundance | Not Significant |
| Low (vs. High) Water Clarity | Significant Decrease |
| Water Flow | Not Significant |
| Poor Overall Condition | Significant Increase |
| Severe (vs. Moderate or Absent) Disease | Significant Increase |
| High (vs. Low) Cormorant Abundance | Significant Increase |

**Analyze the Table**

- Compare the results for cormorants in Table 2 to those for terns in Table 3.
- Did the cormorants tend to take the weak fish?
- Double-crested cormorants chase fish underwater. Explain how cormorant abundance might influence their hunting success.

Both types of predators in this study were taking more of the individuals in poor condition than in good condition. Predation pressure could select for individuals that are better able to resist pathogens or find food. However, condition can be influenced by the environment as well as genetics. This would decrease the ability of predators to select for traits that result in better prey condition. When predators such as humans harvest individuals that are in particularly good condition, it might lead to selection against the traits that humans want in that species. For example, if hunting pressure is particularly high on males with large antlers, males that only grow antlers big enough to be effective in male-male fighting might leave more offspring. The influence of predation of community diversity will be discussed in Chapter 17.

**Evaluate the Hypotheses**

- Which hypotheses were supported by these results?
- Which hypotheses were refuted by these results?

**Check Your Understanding**

- Why don't prey species evolve perfect defenses against predators?
- How might the prey choice of predators influence the genetics of their prey?
- Is coevolution more likely to influence predators that are specialized, or those that are generalists? Explain your reasoning.

**Exploiters and the Exploited Influence Each Other's Population Size**

Without their hosts or prey, parasites and predators cannot survive. When exploiter numbers go down, the populations of their victims increase (if there are no other limiting factors). When victim populations are high, this can allow exploiter populations to increase. An increase in exploiters will drive victim populations down again. A visual model shows that exploiters and their victims will influence each other's population sizes to cause a continuing cycle (Figure 14). The equations that lead to this model are explained in **Model Skill: The Lotka-Volterra Model**. In reality, other factors can influence populations of predators and prey, disrupting the cycle.

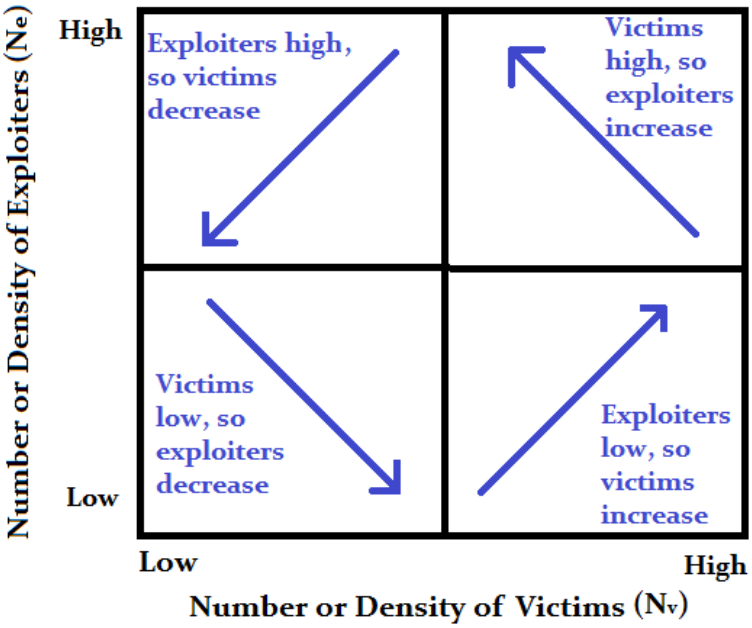



Figure 14. Influence of exploiters and victims on each other's populations. To learn about the equations behind the model, see **Taking It Further: Lotka-Volterra Equations**

**Model Skill: The Lotka-Volterra Model**

The Lotka-Volterra model is used to look at interactions between species. It assumes that the only control on victim species is exploitation and that the only control on exploiter species is the supply of victims. The model also assumes only one species of each. The model predicts repeating predator-prey cycles (Figure 15).

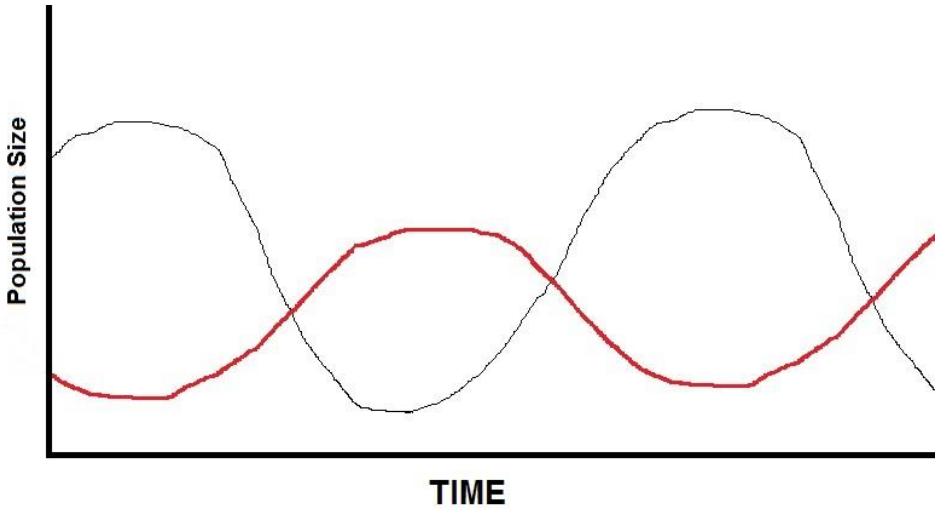



Figure 15. Predictions of the Lotka-Volterra model. Predators and prey are on different scales. There will usually be many more prey individuals.

These cycles continue indefinitely. In reality, the assumptions of the model are often violated, but the models can still useful in understanding predatory-prey dynamics. One key feature is that predator numbers will lag behind prey numbers. When prey become common, it takes time for predators to reproduce more. Lag time will be less if predators merely travel to the area with abundant food, or switch to the abundant prey from another prey.

A researcher collected information on lemmings (small rodents) and ermine (small weasels) in an area of Greenland (Table 4).The methods for obtaining the numbers were a bit different for the two species, but the pattern of increase and decrease are more important than the actual numbers. Add the data to Figure 16. Do these patterns support the predictions of the Lotka-Volterra model?

**Continued**

**Model Skill: The Lotka-Volterra Model, cont.**

Table 4. Lemming and stoat populations in North East Greenland. Data from: Sittler, B (1995). Response of stoats (Mustela erminea) to a fluctuating lemming (Dicrostonyx groenlandicus) population in North East Greenland: Preliminary results from a long-term study. *Ann. Zool. Fennici*, 32:79-92.

| Winter | Lemmings per 1000 ha | Stoats |
|---|---|---|
| 1987-88 | 149 | 11 |
| 88-89 | 1270 | 3 |
| 89-90 | 3687 | 4 |
| 90-91 | 282 | 28 |
| 91-92 | 105 | 15 |
| 92-93 | 145 | 0 |

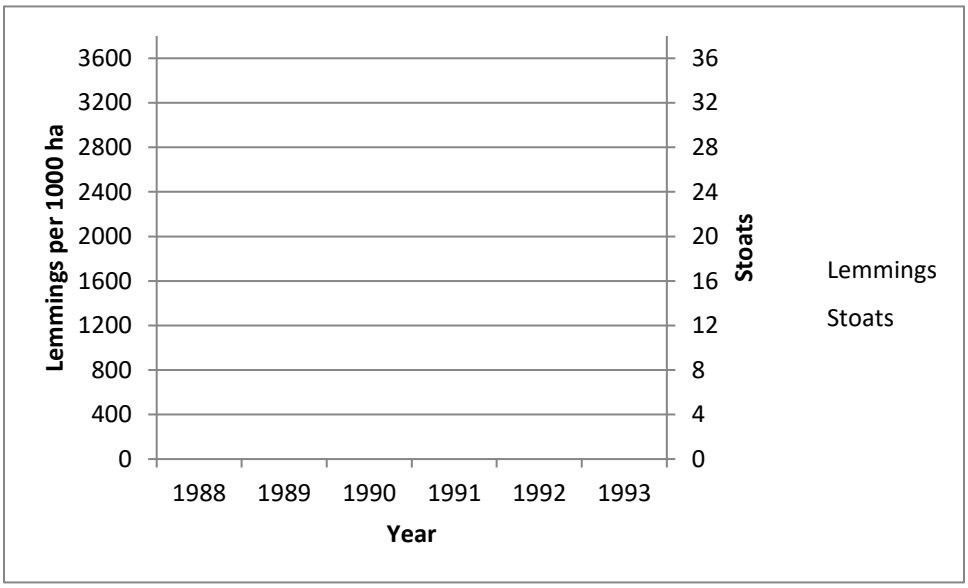
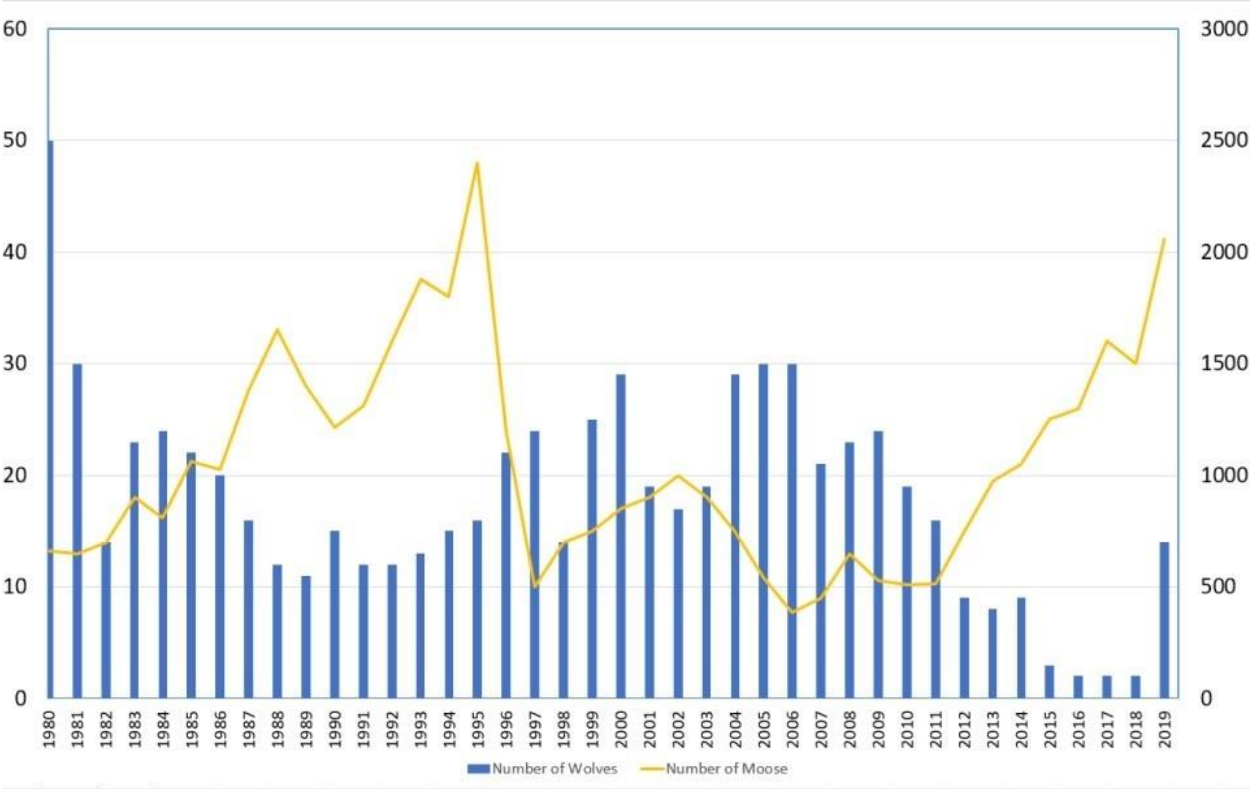



Figure 16. Blank for graph for entering data from lemming (*Dicrostonyx groenlandicus*) and stoat (*Mustela erminea*) populations.

Isle Royale is a US National Park that is home to both moose and wolves. These populations have been studied intensively for decades. Consider some of the reasons that populations might change (review Chapter 12, if necessary). In considering the moose, you probably thought about factors like their food supply, disease, weather patterns, parasites, and predators. When considering the wolves, you probably though about food supply, weather, parasites, and disease. All these factors can be important. Because predators and prey can have a major influence on each other's population size, it is useful to graph their numbers together (Figure 17). Each wolf will eat many moose in its life, so the moose population must be much larger than the wolf population (see Chapter 5). Two Y-axes, each of which has its own scale, makes it possible to see both populations in detail.




https://www.nps.gov/isro/learn/nature/wolf-moose-populations.htm

Figure 17. Population dynamics of wolves (*Canis lupus*) and moose (*Alces alces*) on Isle Royale, 1980-2019. Wolf population and moose populations are on different axes due to the difference in scale. Additional wolves were released on the island in 2018.

**Analyze the Figure**

- When were moose numbers increasing exponentially?
- When were wolf numbers crashing?
- Do high moose numbers usually happen when wolf numbers are high or low?

In some ways, this example supports the predictions of the Lotka-Volterra models, but the pattern is much more complex. Several factors have influenced these populations. Canine parvo-virus (a pathogen) was spread to wolves by domestic dogs in 1980. Moose suffered from ticks, bad weather, and low food supplies in 1996. Inbreeding in the wolf population may also have limited wolf numbers. Wolves were introduced to the island when the population became unsustainable, starting in 2018. In any population, factors other than just numbers of exploiters and victims will probably influence the population cycles of both.

**Taking It Further: Lotka-Volterra Equations**

One way to set up the Lotka-Volterra model is to look at changes in species separately. We can do this using approximations of the actual differential equations:

$$\textbf{Increase in individuals of victim species} = r_v(N_v) - LN_vN_e$$

Where:

- $r_v$ = per capita reproductive rate of victims = how many offspring are produced by each individual in the victim species population. For species with separate sexes and roughly equal numbers of males and females, this would be the average number of offspring per female divided by two (because the males in the population wouldn't produce offspring)
- $N_v$ = number of individuals of the victim species
- L = lethality, the proportion of kills when an exploiter meets a victim. If 10% of predator-prey encounters results in a dead prey, this rate would be 0.1.
- $N_e$ = number of individuals of the exploiter species

The first term, $r_v(N_v)$, states that the number of new individuals of the victim species will be a function of the number of victims and the per capita reproductive rate of victims.

The second term, $LN_vN_e$, accounts for losses of victims to predation. The more victims or exploiters, the more often they will meet. The lethality term indicates how often one of these meetings will end in the death of a victim.

This equation assumes that members of the victim species die only as a result of exploitation by the predator or prey species. In reality, some individuals will starve, be killed by other predators or parasites, or die from accidents. Some may even die of old age.

Another equation is used to predict the number of predators or parasites of a given species.

$$\textbf{Increase in individuals of Exploiter species} = cLN_vN_e - d_eN_e$$

Where:

- c = number of victims that an exploiter must exploit to get enough energy and nutrients to produce one exploiter offspring. If a predator had to exploit 100 extra prey for each offspring produced, this rate would be 100.
- L = lethality, the proportion of kills when an exploiter meets a victim.
- $N_v$ = number of individuals of the victim species
- $N_e$ = number of exploiters
- $d_e$ = per capita death rate of exploiters

**Continued**

**Taking It Further: Lotka-Volterra Equations, cont.**

The first term, $cLN_vN_e$, predicts the number of new exploiter offspring if the only limit on their population increase were the parents' success at exploiting victims. It ignores any biological limit on the ability of the parent to have offspring. In reality, this assumption may be violated when exploiters are very successful, but cannot reproduce rapidly enough to take advantage of their success. The second term accounts for exploiter deaths due to old age or other factors. Both of these equations can be used with calculus to produce the population curves for predator and prey or parasites and hosts that are shown in Figure 15.

Laboratory experiments that involved predators and prey in simple environments usually resulted in predators killing all the prey. When safe refuges were introduced, populations tended to cycle. The refuges acted like the protected zones described in Chapter 10. They were the source of individuals that could repopulate the larger area when predator numbers went down. Refuges may not contain necessary resources, and there may be competition for them, so individuals will be forced into the non-refuge areas. In general, exploiters and victims have long-term population cycles that influence each other without either species going extinct. This is true even when we would prefer the victim species to disappear (see **Why It Matters: Biological Control of Invasive Species**).

Some species influence their victims more than others. If predators are killing individuals that would die soon anyway—such as prey that are in poor condition—the predators may not decrease the population size of the prey much. The number of individuals killed by predators might be nearly the same as the number of individuals that would have died of disease, starvation, or other conditions that made them vulnerable to predation.

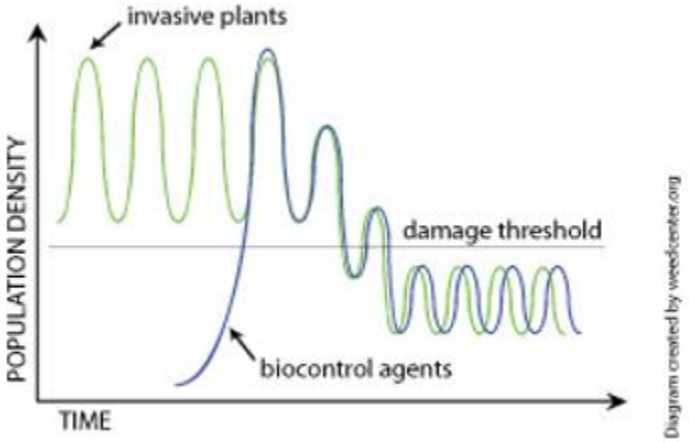
If predators are killing individuals that are in good condition, this will probably decrease population size much more. The deaths due to predation would add to deaths from other causes instead of replacing them.

Some individuals influence population numbers more than others. For example, killing long-lived trees just as they begin producing viable seeds can reduce tree reproduction for years. Killing a dominant male in a species with a polygynous mating system may disrupt the social system. Other males may fight and kill each other. New males may kill all the offspring of the old male.

**Check Your Understanding**

- Why don't exploiters usually drive their victims to extinction?
- Which will usually come first, an increase in predator numbers or an increase in prey numbers? Explain your answer.
- Why don't natural populations always fit the Lotka-Volterra model? What assumptions are usually violated?

**Why It Matters: Biological Control of Invasive Species**




http://www.fws.gov/invasives/stafftrainingmodule/methods/biological/impacts.html

Figure 18. Population dynamics of invasive species and exploiter species introduced to control them.

When a species is introduced to a new habitat, it may be unable to survive because it cannot tolerate the climate, obtain sufficient resources, or coexist with other species that are already there. However, if it can survive, it may have an advantage over native species. The introduced species may have left its exploiters behind. It can then become invasive, taking over area and resources, and driving native species to extinction. It shares no recent evolutionary history with its new neighbors, so there has been no “arms race” with local species.

When invasive species are established in a new area, it may be impossible to remove them. Several invasive plants have been introduced to the US, on purpose or accidentally. For example, early European settlers planted St. John’s wort for medicinal purposes. It spread across rangelands, making grazing animals sick. In the 1940’s insects were imported from Australia—part of the plant’s native range—to successfully control the plant.

Biocontrol agents have been used successfully to reduce the numbers of invasive plants. They do not completely eradicate the invaders because as the host plants are destroyed, the space and resources for the exploiter species declines as well (Figure 18). However, keeping the numbers of the invaders low can allow native species to coexist with the invaders.

- Are the risks of importing exploiter species worth the potential benefits?
- Why protect native species against invasive species?
- Do some invasive species improve the environment?

**Interactions Shift Between Categories**

The costs and benefits shown in Table 1 are useful in understanding species interactions. But relationships between species can be complicated. Costs and benefits can depend on the situation. For example, when nitrogen is low in soil, a plant may benefit by feeding sugar to bacteria that can provide usable nitrogen (see Chapter 5). The interaction would be mutualism. But if nitrogen increases, the nitrogen-fixing bacteria become parasites. Tapeworms in shark guts seem like classic parasites, stealing nutrients from their hosts. But some remove toxic metals that would poison the shark, making them possible mutualists. It can be difficult to measure costs and benefits. How would an ecologist balance the benefit of removing toxins with the loss of nutrients? What if food is not limiting for the shark? What if the shark is likely to die before it accumulates enough heavy metals to harm it? It is still useful to think about categories of interactions, but we can understand these interactions better if we think about benefits and costs in a continuum (Figure 19).

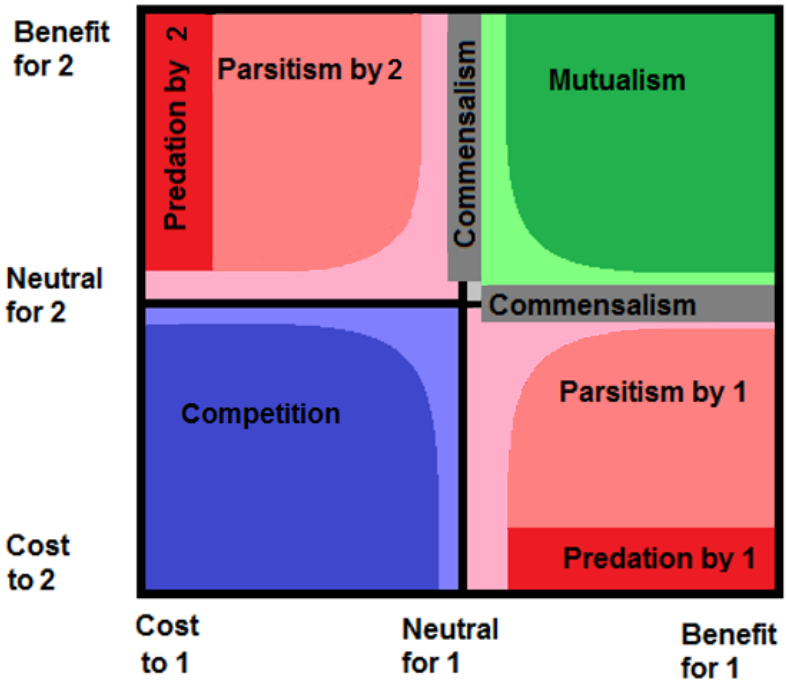



Figure 19. A model of costs and benefits in interactions. Interactions in the lower left quadrant involve costs to both species. The lines in the middle of the quadrants indicate no net costs or benefits. Lighter shading indicates an area where it is difficult to categorize the interactions.

**Analyze the Figure**

- If an interaction is usually parasitism by species 1, but the cost to species 2 approaches zero, what type of interaction would it become?
- Describe a situation in which it would be difficult to categorize an interaction.

**Check Your Understanding**

- Why is it sometimes difficult to categorize relationships such as predation and parasitism?
- If people can die from malaria, does this make the organism that causes malaria a predator? Explain your answer in terms of costs, benefits, and mortality.

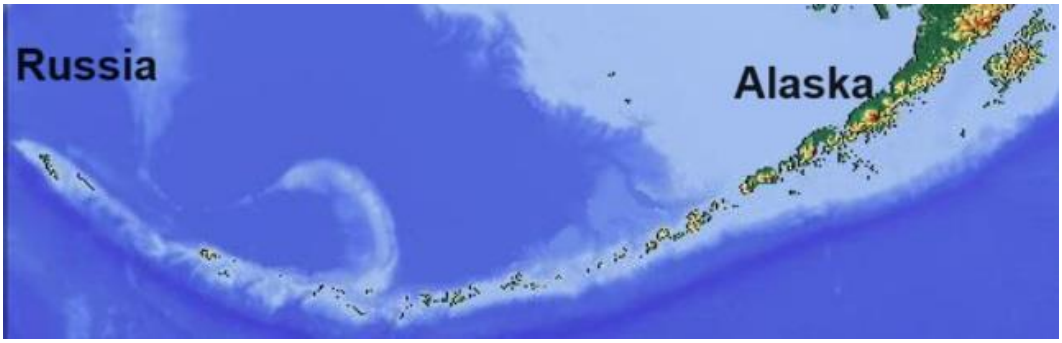
## Keystone Species Can Trigger Trophic Cascades

**Keystone species** influence communities or ecosystems dramatically, even though they have proportionately small numbers. Top predators are usually a small fraction of the individuals in a community because energy is lost at each trophic level (described in Chapter 5). But removing or adding these keystone predators can dramatically change the populations of other species, community diversity, or ecosystem processes. These changes are called **trophic cascades** because the influence of the top trophic level causes changes throughout the other trophic levels.

Arctic foxes (Figure 20) were introduced to many of Alaska's Aleutian Islands (Figure 21) over 100 years ago by hunters intending to harvest the foxes for their fur. Other islands have no foxes. This difference in top predators provides an opportunity to test the hypothesis that arctic foxes caused trophic cascades on islands.

Photo by Ansgar Walk, CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=905259

Figure 20. Arctic fox (*Alopex lagopus*).



Modified from: https://en.wikipedia.org/wiki/Aleutian_Islands#/media/File:Aleuten_Lage-blank.png

Figure 21. The Aleutian Island chain stretches between Alaska and Russia.

Researchers compared 9 islands of each type. They chose the islands so that pairs of fox-infested and fox-free islands were similar in size and location. They found significant differences between the fox-free islands and the fox-infested islands, including differences in the plant community, nutrient levels, and density of seabirds (Table 5). Before the introduction of foxes, several species of seabirds bred on all the Aleutian Islands in the study. Islands without foxes still have large seabird colonies. Foxes prey on these birds, so it is not surprising that seabird numbers were much lower on fox-infested islands. What might be less obvious is why nutrient levels would be much lower on islands with foxes. The seabirds have a critical role in nutrient cycling. The birds feed on marine fish and zooplankton. They then return to the island. The birds transfer nutrients from the marine species when they defecate their guano on the islands.

Table 5. Comparison of Aleutian Islands with and without arctic foxes. Differences were statistically significant. Source: Croll, D. A., Maron, J. L., Estes, J. A., Danner, E. M., & Byrd, G. V. (2005). Introduced predators transform subarctic islands from grassland to tundra. *Science*, *307*(5717), 1959-1961.

| | **Fox-infested** | **Fox-free** |
|---|---|---|
| Seabird density | Low | High |
| Total Soil phosphorus | Low | High |
| Grass biomass | Low | High |
| Shrub biomass | Moderate | Low |
| Plant nitrogen | Lower | Higher |

Researchers tested island soil, plants, birds, and invertebrates for a specific isotope of nitrogen (Delta $^{15}N$) that is found in marine sources, but not fixed by soil microbes. They found significant differences in the source of nitrogen between the islands with and without foxes. When foxes were absent, seabirds carried nutrients from marine sources to islands, allowing the islands to support grasslands. When a keystone species—the arctic fox— was added to the community, it created a trophic cascade. The foxes ate seabirds, greatly reducing their numbers. This caused a major decrease in nutrient additions to islands with foxes. The plant communities were able to produce significantly less biomass on the fox-infested islands. Grasses were especially affected

by the drop in nutrient levels, allowing other plants to out-compete them. The islands with foxes were transformed from grasslands to tundras.

**Check Your Understanding**

- Grasses are an important part of the Aleutian Island ecosystem. Why aren't they considered keystone species?
- How is a trophic cascade different from a predator-prey cycle?

# Key Concepts

- A species' niche is defined by its interactions with other species and the abiotic environment.
- Both predators and parasites exploit other species. In predation, the prey species dies. In parasitism, the host usually stays alive, though it may die incidentally.
- Exploiter species and their victims influence each other's population cycles. Exploiter numbers tend to lag behind victim numbers.
- Exploiters and victims influence each other's evolution. Traits that give one species an advantage create selection pressure for traits in the other species.
- The costs and benefits of interactions can vary in different circumstances.
- Keystone species are small in number, but important in their impact on ecosystems. They can cause trophic cascades.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately analyze relationships between species*
2. *Make reasonable predictions about the influences of exploitation on populations*
3. *Draw reasonable conclusions about evolutionary history of exploitative interactions*

1. Refer to the lemming and stoat data that you graphed in figure 16.
   A. Describe what happened to lemming and stoat numbers between 1989 and 1990.
   B. Explain this pattern using predator-prey dynamics.
   C. Describe what happened to lemming and stoat numbers between 1990 and 1993.
   D. Explain this pattern using predator-prey dynamics.
   E. Make a valid prediction about the trends for stoat and lemming numbers from 1993 to 1995 and explain your prediction.
   *(Learning Outcomes 1 & 2)*

2. In the 1930s, Australian sugarcane growers lost crops to the cane grub. In response, cane toads (*Bufo marinus*) were introduced to Australia. The cane toads immediately began to spread, outcompeting local species. They never ate the cane grubs, but they do eat almost any animal that fits in their mouths. Local predators die when they try to eat the cane toads, which have poison glands. Cane toads originated in Central and South America, where many predators—such as caimans and ibis—eat them successfully.

A. Explain how resistance to the toxin could have developed in native predators of the cane toad (such as caimans). Avoid Lamarckian or teleological explanations (see Misconceptions in Chapter 4).
B. Explain why cane toads were such successful invaders.
C. Is it likely that Australian predators will develop resistance to the cane toad toxins? Explain your prediction, including any limitations. *(Learning Outcomes 1- 3)*

3. Kleptoparasites get their name from stealing. For example, frigatebirds are large birds that fish in the ocean. They also steal fish from other birds. Why is this considered parasitism rather than competition for the fish? Think carefully about costs and benefits to the frigatebirds and whether they are better off when there are victims around. *(Learning Outcome 1)*

4. Many people die from malaria every year. Why is the organism that causes malaria considered a parasite instead of a predator? *(Learning Outcome 1)*

5. Some new diseases are very deadly but become less deadly over time. How would it benefit the pathogen—not the host—for the pathogen to harm its host less? *(Learning Outcomes 1 & 3)*

6. The African Serengeti is a savannah ecosystem with trees scattered in grassland. Rinderpest virus was once common in the Serengeti and killed both wildlife and domestic animals. Rinderpest was eradicated in the Serengeti in the 1960s to protect domestic cattle. Since being protected from rinderpest, wildebeest have become common in the Serengeti. The wildebeest grazing pressure has made grass fires less common. The decrease in fires allowed more trees to survive the seedling stage. Now tree density is much higher than it was when rinderpest was common. The increase in trees means that more carbon is being stored in Serengeti plants now than before rinderpest eradication.

   A. Is this an example of a trophic cascade? Explain your reasoning.
   B. Are any of the species described in this situation keystone species? Explain your reasoning.

**Unit V: Communities**

# Chapter 15: Balance of Power

## Case Study Part 1: Do Bison Steal Grass from Cattle?

https://commons.wikimedia.org/wiki/File:Bison_bison_bison_GNP_04.jpg

Figure 1. Bison (*Bison bison*) live in the Henry Mountains of Utah, USA.

Many ranchers in southern Utah's Henry Mountains consider bison pests that compete with cattle. The ancestors of the herd were transplanted from Yellowstone National Park in 1941. Some people think that bison should be reduced or eliminated completely from the Henry Mountain area so that cattle will have more to eat. Researchers studied populations and diets of several rangeland species to determine whether bison reduce the profits of ranchers.

This chapter will explore relationships between individuals of different species that do not exploit each other. They may compete with each other for resources, benefit each other, or have little direct influence on each other. The nature of the relationships between these species can shift under different circumstances, making it difficult to correctly predict the outcome of interactions, even when researchers know a lot about individual species.

### Learning from the Case Study

- If cattle and bison both eat grass, does this mean they are competitors?
- Would studying bison and cattle separately in different places reveal whether bison have a negative influence on cattle?

# Learning Outcomes

1. *Accurately analyze relationships between species*
2. *Make reasonable predictions about how costs and benefits influence species interactions and coevolution*
3. *Draw reasonable conclusions about evolutionary relationships between species*

**Vocabulary Toolkit**

**Roots**

Intra = within
Inter = between

**Word Watch List**

**Commensalism**: Interaction in which individuals of one species benefit. Individuals of the other species are neither helped nor harmed measurably
**Mutualism**: Interaction in which individuals of both species benefit
**Facultative mutualism**: One or both species participates in mutualism only under circumstances when it is to their advantage
**Obligate mutualism**: One or both species cannot survive without the mutualism
**Intraspecific competition**: Competition within a species. Individuals are attempting to use the same or similar resources
**Interspecific competition**: Competition between individuals of different species. Individuals are attempting to use the same or similar resources
**Competitive exclusion**: One species out-competes another, eliminating it locally or globally
**Resource partitioning**: Species use resources in different ways, allows coexistence
**Scramble competition**: Competition focused on resource use rather than direct interaction with competitors
**Interference competition**: Competition that involves attempting to directly stop competitors from using resources. It may involve fighting or chemicals
**Median**: Number that divides a data set in half
**Quartile**: Numbers that divide a data set into quarters
**Interquartile range**: Values between quartiles 1 and 3

### Community Interactions Have Varying Costs and Benefits

As discussed in Chapter 13, communities consist of all the organisms in one place. These interactions—and a species' requirements from the physical environment—define its niche. The interactions discussed in Chapter 13 involved exploitation of individuals in one species by individuals in another. Other ways that species interact include competition, mutualism, and commensalism.

While ecologists find it useful to categorize the interactions, the natural world is complex. An interaction that starts as parasitism can evolve into mutualism. Parasites that help their hosts survive longer can increase their own fitness under some circumstances. An interaction that has little or no cost to an individual in some circumstances could have costs or benefits as conditions change. For example, a bird sitting on a tree usually results in no cost or benefit to the tree. However, if the tree is small and a flock of birds lands on it, the tree could be damaged. If the tree is in low-nutrient soil, and a bird regularly defecates under that tree, the tree could benefit from the nutrients added to the soil. If a bird deposits seeds of other plants that grow and remove nutrients from the soil, the tree's fitness may be reduced by the bird's visits.

### Check Your Understanding

- Select a species you know well and describe some ways it might interact with other species.
- Do individuals of the same species always have the same type of relationship? Explain your answer.

### Commensalism Benefits Individuals of one Species

Interactions demonstrate **commensalism** if only one participant benefits, but the other is not harmed or helped. There is no evolutionary pressure on one species involved in the interaction. If a bird has a nest in tree, the bird gains a nesting site that is protected from many predators (Figure 2). If there is no net cost to the tree, there's no "arms race" between the nesting bird and the tree. A small burr that attaches to a grazing bison does not reduce the fitness of the bison, but it allows a plant to spread its seeds. Orchids grow on tree trunks, but do not take any nutrients from the tree or block sunlight getting to the leaves. If an animal sees other animals fleeing, it might flee as well, benefiting from a warning without any cost to the first animals that discovered the danger.

Commensalism can be confused with parasitism because it can be difficult to quantify the costs and benefits to the individuals involved. Remoras are fish that attach themselves to sharks, as well as other large fish, even the occasional diver or other mammal. The remoras benefit from the messy eating habits of the shark and may eat shark feces. They can swim independently but can also let the larger fish do the work. If the remora causes the shark to spend extra energy on swimming, or if the shark's speed or maneuverability were reduced by the remora, this would be parasitism. In the case of smaller sharks, or sick sharks, this might be the case. On the other hand, if the shark benefits when remoras keep the shark and its environment clean, this could be a case of mutualism. For a model of how interactions can shift, see Chapter 14, Figure 19.

http://commons.wikimedia.org/wiki/File:Bird_nest_in_tree_in_Summit_New_Jersey.jpg

Bird nest in a tree.

https://en.wikipedia.org/wiki/Bur#/media/File:Burrs.png

Burrs are seeds that attach to animals. For large animals, carrying burrs has a low cost.

http://en.wikipedia.org/wiki/File:DirkvdM_red_flat_epiphyte.jpg

Orchid growing on a tree trunk.

http://commons.wikimedia.org/wiki/File:Manta-ray_australia.jpg

Remoras attached to the underside of a manta ray. The remoras are right-side-up.

Figure 2. Examples of commensalism.

**Check Your Understanding**

- How is commensalism different from parasitism?
- Why doesn't commensalism usually involve coevolution?
- Provide another example of commensalism.

**Mutualism Benefits Individuals of Both Species**

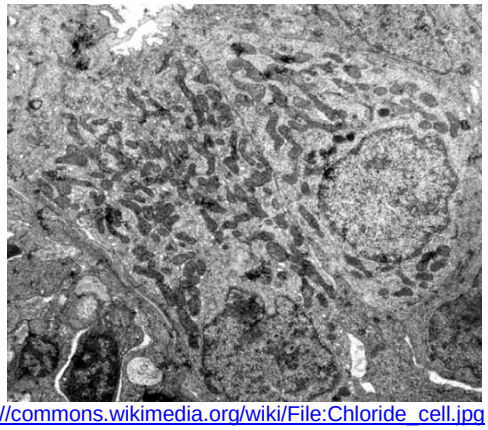
**Mutualism** describes interactions between individuals of different species in which both (or all) individuals in the interaction receive a net benefit. One or all participants may bear costs, but these are lower than the benefits. When the individuals only participate in the interaction under certain conditions, it is called **facultative mutualism**. When one species cannot survive without the other, it is **obligate mutualism**. Mutualism can be obligate for one species, but facultative for the other. Mutualists belong to different species.

**Misconception Alert: Mutualists are cooperating for each other's benefit.**

**FALSE.** Participants in mutualistic relationships are still under selective pressure to maximize their own fitness. For example, imagine that a "biter" mutation caused hungry cleaner fish to occasionally take a bite out of the fish it's cleaning. A biter fish may leave more offspring than a non-biter. We would then expect the "biter" gene to become more common in the cleaner fish. On the other hand, if the large bitten fish chases the biters and occasionally eats them, the "biter" gene would probably be rare.

Arguably the most successful mutualistic relationship is no longer considered mutualism because the players are no longer separate species. Recall from Chapter 4 that all eukaryotic cells contain mitochondria, organelles that are vital in harvesting energy from food (Figure 3). These mitochondria have their own DNA, suggesting that they were once independent organisms. Perhaps they began by parasitizing eukaryotic cells or perhaps eukaryotic cells once preyed on the ancestors of the mitochondria. Mitochondria that lived inside of eukaryotic cells received protection and had a supply of food provided by the eukaryotic cell. If the mitochondria provided their host with more usable energy (ATP) for each sugar molecule, the infected eukaryotic cells would have been much more successful than their competing eukaryotic cells. Each time the eukaryotic cells divided, they would spread mitochondria, making the eukaryotic cell/mitochondria a successful team that outcompeted either organism acting on its own. This relationship is now obligate for eukaryotic cells and mitochondria.

Sea anemones may look like plants, but they are animals. They sting prey with their tentacles, then stuff the stunned prey into their mouths. Clownfish would seem to be risking their lives by swimming among the tentacles of the anemones, but the two species are mutualists. Clownfish live in pairs on their own anemone territory. They are protected from stings by mucus. Predators of the clownfish avoid the anemones. The clownfish protect the anemones from one of their predators, the butterfly fish. Is this mutualism facultative or obligate for the fish and the anemone?



http://commons.wikimedia.org/wiki/File:Chloride_cell.jpg

Eukaryotic cell with many mitochondria from a fish gill.

http://wikimediafoundation.org/wiki/File:A_ocellaris_2_Sesoko_Point_140904_LOWRES.jpg

Sea anemones and clownfish protect each other from predators.

http://commons.wikimedia.org/wiki/File:Ring-Tailed_Lemur_eating.jpg

Ring-tailed lemur eating fruit.

http://www.ecolibrary.org/page/DP162

Ant on bullhorn acacia thorn.

http://commons.wikimedia.org/wiki/File:Kelp_bass_with_streak_cleaner_wrasse.jpg

Cleaner wrasse remove parasites from a larger kelp bass.

http://commons.wikimedia.org/wiki/File:Atta_laevigata_fungus_garden.jpg

Leaf cutter ants tend their crop of fungus.

Figure 3. Examples of mutualism.

Fruits and berries are “bribes” to get animals to move seeds into potential new habitats. They only ripen when the seeds within are ready to be spread. The seeds themselves may even be poisonous. Nuts are also seeds. They may be protected by toxins, but in the evolutionary arms race, some nut eaters have been selected for resistance to the toxins. If the seed-eaters store the seeds, some of those may sprout because the animal storing them may die or forget.

Some species of ant have developed a close mutualism with a thorny tree called the bullhorn acacia. The tree produces special hollow thorns that provide living space for the ants. Instead of receiving nectar from flowers, the ants get nectar from special structures on the tree that seem to have no function other than as ant feeding stations. The ants protect the acacia trees from various animals that would feed off the tree. For the ants, the relationship is obligate because they depend on the acacia for their food and shelter. For the tree, the relationship is facultative because they can survive some damage from herbivores.

Parasite removal is the basis for several mutualistic relationships. On coral reefs, small fish nibble parasites off large fish. These small cleaner wrasse fish even go inside the mouths of the large fish to remove parasites from the mouth and gills. Several species of birds, including the oxpecker, remove parasites from large grazing animals.

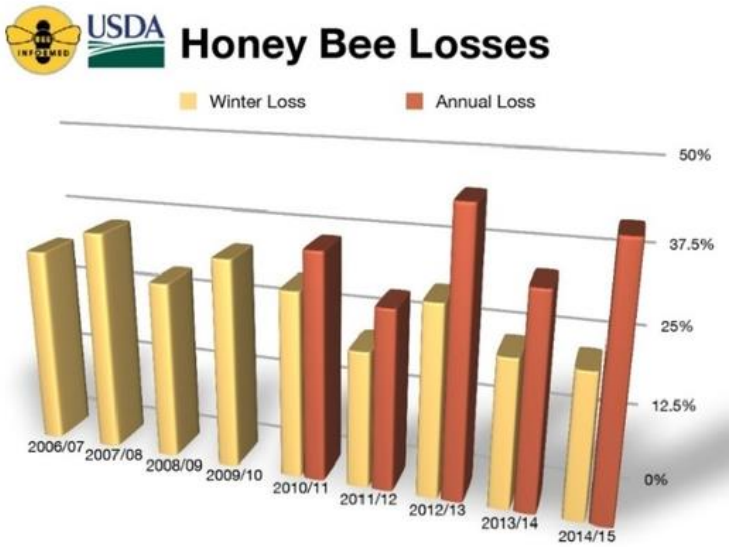
Leafcutter ants cultivate a fungus for their food source. They cut pieces of leaves off plants and take them into their nests. They use them as food for specific fungi that they carefully tend, removing “weeds” and using bacteria to kill pathogens. The ants eat some fungus. The fungi receive habitat, food, care, and protection.

Many species—including some bats, birds, and insects—pollinate plants and gain sugary nectar as a benefit (Figure 4). When pollinators gather nectar from flowers, they also pick up pollen, which contains the plant’s male gametes. Each flower only provides a small amount of nectar, so the animal is forced to move on to another flower. At the next flower, some of the pollen is transferred to the female reproductive parts and the animal picks up more pollen. For a discussion of how our food supplies depend on pollinators, see **Why It Matters: Colony Collapse Disorder**.

https://www.inaturalist.org/photos/14515893

Figure 4. Bat pollinating a flowering plant. The bat’s head picks up pollen as it feeds. Pollen already on its head may also be transferred to the plant as it feeds.

**Why It Matters: Colony Collapse Disorder**




https://www.ars.usda.gov/news-events/news/research-news/2015/bee-survey-lower-winter-losses-higher-summer-losses-increased-total-annual-losses/

Figure 5. Failure rates of agricultural honeybee hives in the US.

Honeybees make honey from nectar and store it, along with pollen, to feed their hive throughout the winter. The queen bee stays in the hive and produces eggs from stored sperm. Sterile female workers defend the hive and collect pollen and nectar. Bees pollinate crops worth billions of dollars, including fruits, nuts, alfalfa, and cotton. Professional beekeepers transport hives of bees to areas when plants are flowering.

During the winter of 2006-2007, beekeepers reported hive failures at rates that had never been seen before (Figure 8). The hives' nurseries and food stores were full. The queens were healthy, but most of the worker bees had disappeared, leaving their hives to die. In the years since, losses have varied. During the 2012-2013 winter, the average hive loss in the US was about 45%. The phenomenon is now known as Colony Collapse Disorder (CCD).

Several hypotheses have been introduced to explain CCD. Some blame pesticides, genetically modified organisms (GMOs), parasitic mites, viruses, intestinal parasites, degraded habitat, poor nutrition, or bee management issues. Some combination of factors may be responsible. The USDA, EPA, and other agencies, along with academic researchers continue to study the issue.

- The European Union announced a test ban on a group of pesticides that some people suspect may cause or contribute to CCD. Should the US ban these pesticides too?
- Should we wait for more data before regulating GMOs and pesticides?
- Some data indicate that colonies in areas with high-protein pollen have higher survival rates. Should the USDA encourage growing more plants with high-protein pollen?
- How would a loss of bees influence the US economy?

It is important to remember that selection is not happening between the individuals of different species in a mutualistic interaction; it is happening between members of the same species. For example, a bat-pollinated plant that "cheated" by producing flowers with no nectar could potentially leave more offspring than a flowering plant that produced a lot of nectar and therefore had less energy for other activities, such as making pollen. The evolutionary importance of the cheating is not that the bat was cheated by the flowering plant, it is that the other flowering plants were cheated. Fitness differences between individuals of the same species in a population are the basis for natural selection. However, responses by the bat can change the fitness values of nectar production in the plants.

One possible outcome of the plant cheating is that the genes for producing no nectar would become more common as those plants left more offspring. The "no nectar" alleles could spread until there was no mutualism. Bats might then be parasitized by the plants, moving pollen without getting a reward. However, there would be selection pressure that favored bats with genes that caused them to avoid the cheater flowers. These flowers would then not be pollinated and would probably become rare.

Another possibility is that bats would learn to avoid that type of flower (learning would not be the cause or result of a genetic change in the bats). If bats punished flowers that did not produce enough food by avoiding them, the fitness of cheater plants would decrease. We would expect cheater genes to become less common in the population of flowering plants. So punishment of cheaters, either due to learning or genetic changes, maintains mutualistic relationships despite individuals being selected for increasing their own fitness. Terms such as "cheat" and "punish" are anthropomorphic, but they can be useful in understanding costs and benefits. For a discussion of how conflict between pollinators and plants can lead to new species of plants and pollinators, see **Evolutionary Perspective: Coevolution, Pollinators, and Speciation**. For more on cheating and punishment in mutualism, see **Testing Hypotheses: Do soybeans punish cheating in rhizobia?**

**Check Your Understanding**

- Is mutualism cooperation between species?
- What prevents "cheating" in mutualism?
- Do participants in mutualism have to receive benefits?

**Evolutionary Perspective: Coevolution, Pollinators, and Speciation**

Hummingbirds and the plants they pollinate are mutualists. The flowering plant benefits from having its pollen spread to the female parts of other plants in its population. The birds eat the sugar-rich nectar provided by the plants. As discussed in the bat pollination example, plant and pollinator depend on each other, but they have conflicting interests. A plant will have a higher fitness if it minimizes the nectar it makes and maximizes the delivery of its pollen to the correct place on another plant of its species. A hummingbird will have a higher fitness if it gets the maximum amount of calories and nutrients from the flowers while minimizes its time and energy costs.

A mutation that made a plant's the flowers longer would limit access to its nectar. Only birds with long bills could drink the nectar. These birds would benefit by having few competitors. The flower would benefit when its pollinators specialized on it. Plants with mutations leading to longer flowers would lead to selection for birds with mutations for longer bills.

Having specific pollinators reduces gene flow between plant populations. This can lead to macroevolution (splitting into new species) in the plants. Hummingbirds specializing in specific flowers may be isolated in space from other hummingbird populations. If the flowers bloom at different times, this may influence the breeding season of different populations. Over time, this isolation can lead to speciation in the hummingbirds. The earliest fossil evidence of hummingbirds is over 22 million years old. In that time, they have diverged into hundreds of species.

Source: http://commons.wikimedia.org/wiki/File:Sword-billed_Hummingbird(Ensifera_ensifera).jpg

Figure 6. Sword-billed hummingbird at a feeder. This bird pollinates plants with very long flowers.

**Testing Hypotheses: Do soybeans punish cheating in rhizobia?**

As discussed in Chapter 5, plants cannot use atmospheric nitrogen. The major natural pathway for atmospheric $N_2$ to become fixed into ammonium or ammonia that plants can use is through the action of nitrogen-fixing bacteria. These bacteria live in root nodules of legumes, such as clover, soybeans, and peanuts. The legumes spend energy fixing much more nitrogen than they need themselves, but the plants with root nodules provide the bacteria with carbohydrates made in photosynthesis and related reactions.

It is tempting to view this symbiotic interaction as the bacteria and plant cooperating for the benefit of both. If all the rhizobia on one plant were descended from the same founders, both plant and rhizobia would be selected for cooperation. If the plant had plenty of usable nitrogen and grew well, it would be able to provide more food for the bacteria, allowing them to grow and reproduce faster. Several strains of rhizobia may colonize the roots of plants, and some fix little or no nitrogen. When one strain is using energy to fix nitrogen, and the other strain is cheating by taking the food, but fixing little nitrogen, the cheater bacteria can invest more in growth and reproduction, potentially outcompeting the "honest" nitrogen-fixing bacteria.

Kiers et al. (2003) compared this situation to the Tragedy of the Commons discussed in Chapter 2. When individuals behave selfishly in their use of a "public" resource, all the individuals lose. In this case, the plant is like the common grazing area, and the strains of bacteria that do not fix nitrogen are like the individuals that used more than their share of the available grazing. Researchers tested the hypothesis that plants would punish cheating rhizobia.

Their hypotheses were:

1. Plants will punish cheating rhizobia (sanctions hypothesis).
2. Plants will not punish cheating rhizobia (null hypothesis).

One challenge was how to make the rhizobia cheat. Other researchers had compared plant responses to different strains of rhizobia with different levels of nitrogen fixing. This introduces possible confounding variables because the rhizobia may differ in many ways. The researchers solved the problem by using rhizobia that normally fix nitrogen but not giving the rhizobia any atmospheric nitrogen to fix. Recall that the air around us is usually roughly 80% nitrogen and 20% oxygen, plus other gases. Researchers provided "air" that had either 80% nitrogen and 20% oxygen or "air" that was 80% argon (an inert gas) and 20% oxygen. They then measured the growth of root nodules and their oxygen levels. In one test entire plants were exposed to the nitrogen mix or the argon mix (whole plant treatment). In another test, individual plants received the two different mixes in opposite halves of the plant (split plant treatment). In a third, individual nodules received different air mixtures.

If plants do not punish cheating (the null hypothesis). We would predict that cheating rhizobia would have higher rates of growth and reproduction because they would not be using energy to fix nitrogen. Performance of rhizobia was measured by testing the number of rhizobia in or near nodules (Figure 7).

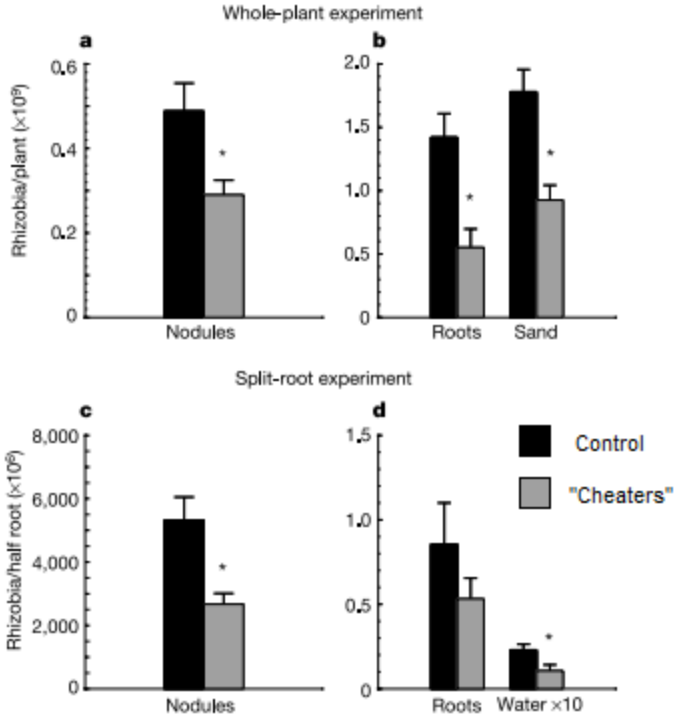



Figure 7. Response of rhizobia (*Bradyrhizobium japonicum*) when "forced to cheat" by being exposed to air with little or no nitrogen. In **a** and **b**, the entire plant was exposed to one of the air mixes. In **c** and **d**, the roots of one soybean plant (*Glycine max*) received two different air mixes. In **b** and **c**, rhizobia were counted. Asterisks denote significant differences between control and "cheater" rhizobia. Modified from: Kiers, E. T., Rousseau, R. A., West, S. A., & Denison, R. F. (2003). Host sanctions and the legume–rhizobium mutualism. *Nature*, *425*(6953), 78-81.

**Analyze the Figure**

- Which rhizobia (cheaters or controls) had more growth and reproduction?
- Can individual plants punish rhizobia in some roots and not others?
- Which hypothesis is supported by the data?

How might plants punish rhizobia? Recall from Chapter 5 that photosynthesis produces both glucose and oxygen. Cellular respiration by rhizobia consumes both glucose and oxygen. If rhizobia were provided with more carbohydrates and were breaking these down, we would predict a decrease in their oxygen levels. On the other hand, limiting oxygen delivery to rhizobia would prevent the rhizobia from metabolizing the carbohydrates. Kiers et al. (2003) identified three hypotheses:

- Plants attack cheaters directly with chemicals.
- Plants decrease the amount of carbohydrate delivered to rhizobia.
- Plants decrease the amount of oxygen delivered to rhizobia.

Researchers measured oxygen levels within nodules and escaping from nodules (Figure 8).

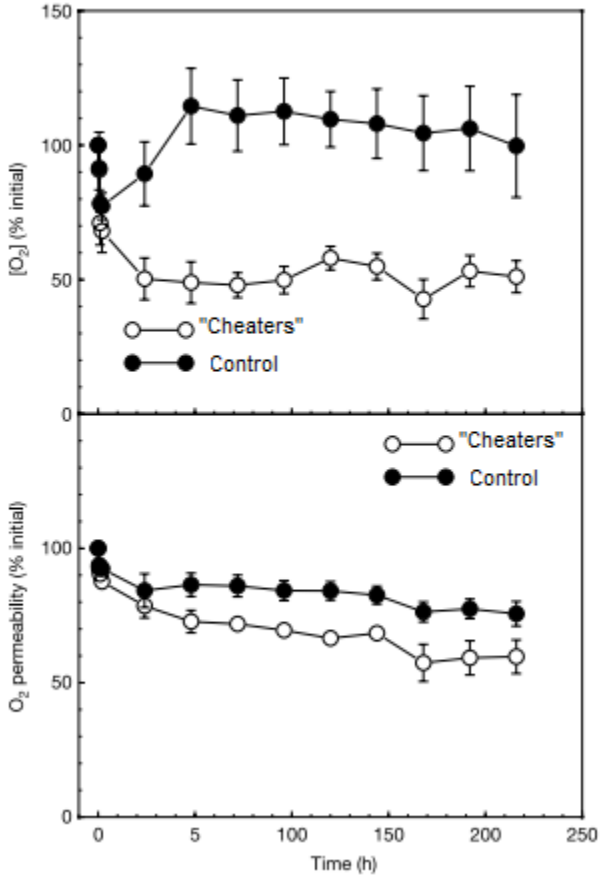



Figure 8. Oxygen concentration and permeability of rhizobia nodules when rhizobia were "forced to cheat" by being exposed to air with little or no nitrogen. Differences between the treatments were significant by day 2. Modified from: Kiers, E. T., Rousseau, R. A., West, S. A., & Denison, R. F. (2003). Host sanctions and the legume–rhizobium mutualism. *Nature*, *425*(6953), 78-81.

**Analyze the Figure**

- Which rhizobia (cheaters or controls) had greater oxygen concentration?
- Can individual plants punish rhizobia in some roots and not others?

**Evaluate the Hypotheses**

- Which hypothesis was supported by these results?
- Which hypothesis was refuted by these results?
- Which hypothesis was not tested by these measurements?

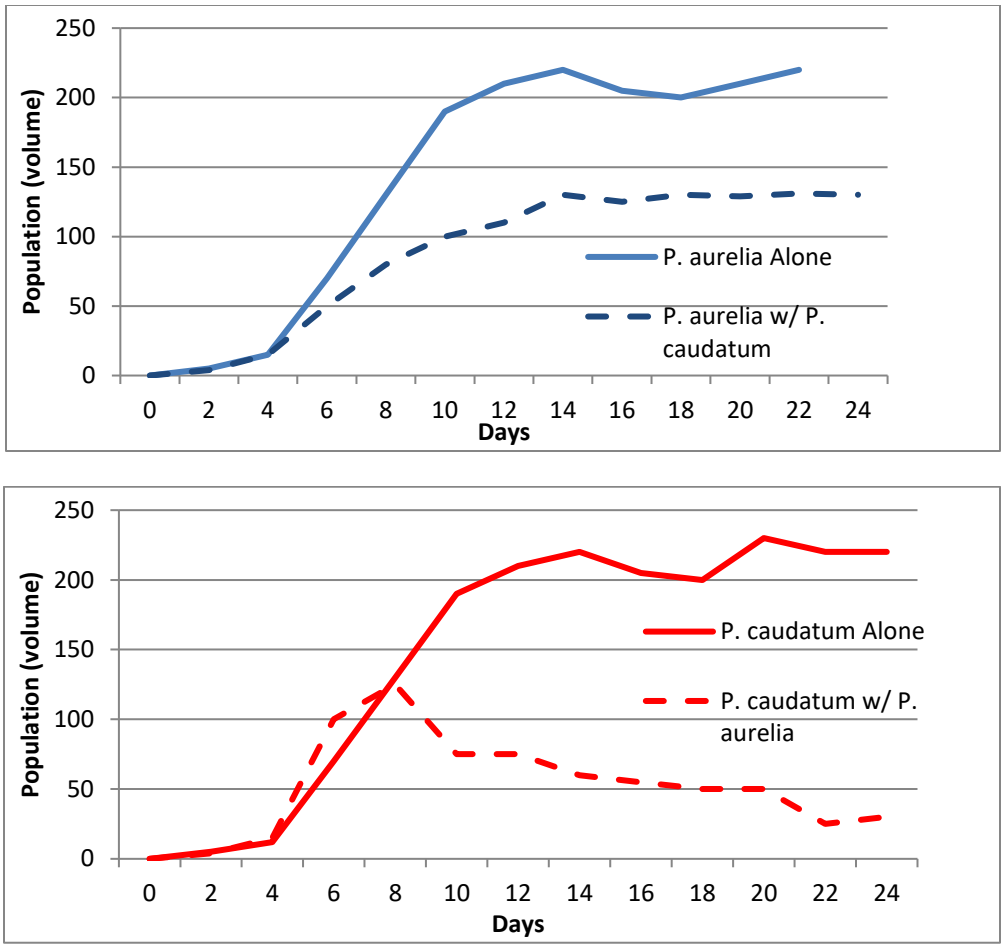
### Competition Results When Individuals Use Similar Resources

Individuals of some species compete because they use the same (or similar) resources. If you have a garden, you probably remove weeds so that they do not take light, water, and nutrients from the plants you are trying to grow. The more closely related species are, the more likely they are to use the same resources. Competition between members of the same species is called **intraspecific competition** (see Chapter 11). It is why you cannot crowd too many tomato plants into the same space (see **Do Try this at Home: Plant competition**). **Interspecific competition** can also exist between individuals of different species, even those in different kingdoms. Competition creates costs for all of the competing individuals, even the "winners," which may lose resources, be damaged, and have to invest in structures, chemicals, or behaviors to defeat their competitors. This is why you weed a garden.

**Do Try this at Home: Plant competition**

Gardeners typically weed their gardens, removing less-favored plants to reduce interspecific competition. Is this a good practice or a waste of time and energy? Get several identical containers (plastic food and beverage containers work well), fill them with potting soil, and plant seeds of different species at different densities. Record some measure of plant growth for several days. Do plants with competitors of other species have slower growth? Does this effect change with time? Does intraspecific competition have a greater influence than interspecific competition?

Some early observations and experiments demonstrated that in any competition, there will be winners and losers. In the 1930's a biologist tested these ideas in controlled conditions using single-celled organisms such as *Paramecia*. One experiment consisted of growing two different species of *Paramecia* in containers and measuring the population size. Some contained only one species. In others, the species were mixed (Figure 9).




Based on data from: Gause, G.F. (1934). The Struggle for Existence. Baltimore: Williams & Wilkins.

Figure 9. Effect of competition on population size (measured as volume) of two species of Paramecium.

**Analyze the Figure**

- Which had a higher population by the end of the study, *P. aurelia* grown alone, or *P. aurelia* grown with *P. caudatum*?
- Which had a higher population by the end of the study, *P. aurelia* grown with *P. caudatum* or *P. caudatum* grown with *P. aurelia*?
- Why was the effect of interspecific competition on *P. caudatum* only obvious after about 8 days?

Both species had smaller populations when the other species was present, indicating competition between the species. However, one species was almost completely eliminated in the mixed-species treatment. This demonstrates **competitive exclusion**—when two or more species use the same resources the same way, one species will out-compete the other species.

You may wonder why there would be so many competing species if one species is always a better competitor. The answer is that the specific conditions determine which species is the "winner." Subtle changes in food concentration and other factors changed which *Paramecium* species did better in competition experiments. Recall from Chapter 4 that local differences in conditions are one of the main drivers of macroevolution. One set of conditions favors individuals with specific traits. A slightly different set of conditions favors individuals with other traits. The natural world has varying levels of resources and environmental conditions, so the species that wins in one area may be the loser in another area.

Species may coexist because they use resources in different ways. One species may specialize on slightly different food types or microclimates. This is called **niche partitioning** (Figure 10). Traits that reduce competition between species do not occur because the species "agreed" to do things differently or use different habitats. Individuals with traits that put them in more intense competition with others leave fewer offspring than individuals that overlap less with their competitors. The alleles for the traits were created by random mutation.

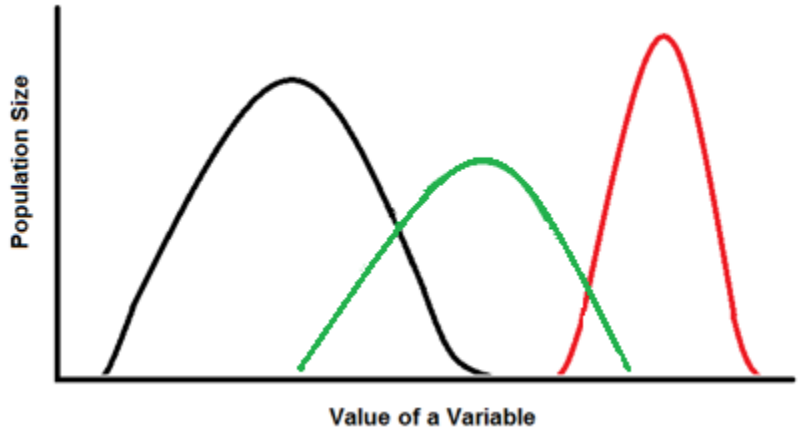



Figure 10. Hypothetical example of niche partitioning. Each color represents a different species. The variable in question might be related to habitat (such as climate, soil type, or water chemistry), type of food, or behavior. Individuals of different species might specialize in different values of the variable.

**Analyze the Figure**

- When species overlap in their use of a variable, what happens to their population size?
- What would you predict will happen to the distribution of the species in green? Will it be likely to increase or decrease its variation in how it uses the variable?
- What do you predict would happen if the species represented by black disappeared? How might the other species be affected?

**Scramble competition** (as described in Chapter 11 for intraspecific competition) means using the same or similar resources without the need to interact directly with competitors. Pollinators of different species might be visiting the same type of flowers, attempting to harvest nectar. Filter feeders might be attempting to remove food particles from water in the same area.

**Interference competition** involves physical or chemical "fighting" or threats. This would include a hyena stealing a dead antelope from vultures, a fish displaying over a food patch to drive off other fish, or a creosote bush putting chemicals into the ground that prevent other plants from growing near it (Figure 11, also see discussion of dispersed distribution in Chapter 10).

http://www.flickr.com/photos/string_bass_dave/5583907943/in/photostream/

Figure 11. Creosote bush roots produce chemicals that inhibit other plants. This creates spacing between the bushes.

Most antibiotics are chemicals that bacteria make to kill competing types of bacteria, fungi, or other organisms (Figure 12). We may synthesize the chemicals now, but they were originally created as the result of an evolutionary arms race between microbes. For more on how we benefit from competition between microbes, see **Make the Medical Connection: Resident Bacteria and Health**.

http://commons.wikimedia.org/wiki/File:Antibiotic_sensitvity_and_resistance.JPG

Figure 12. Bacteria produce antibiotics that inhibit other bacteria. The white disks are paper containing antibiotics. The off-white material is a layer of bacteria. The clear areas show absence of bacteria. In the dish on the left, bacteria are sensitive to the antibiotics. In the dish on the right, some bacteria have evolved a resistance to the antibiotics.

**Make the Medical Connection: Resident Bacteria and Health**

You have trillions of your own cells in your body, but you are host to even more bacterial cells of various species that live in and on your body. You are the most important resource in the world to these bacteria. They have evolved various traits that allow them to fight off the bacterial invaders that might make you ill, because these are their competitors. If you have ever taken antibiotics, you may have experienced infections by non-resident organisms that moved in when some of your resident bacteria were wiped out. Our understanding of the community ecology of microbes on our bodies is still rather poor. This may be an area of rapid medical progress as techniques for studying the bacteria improve.

**Check Your Understanding**

- Do individuals of either species benefit from competition?
- Does competition always involve threats or fighting?
- Why don't competitors always drive each other to extinction?

**Case Study Part 2: How might Bison and Cattle Compete?**

Bison and cattle are such close relatives that they can interbreed. Close relatives usually have similar needs and compete for resources. Neither bison nor cattle are territorial, but they could potentially fight over a patch of food or water. Fighting would be interference competition. As suggested in part one, cattle and bison might both be eating the same kind of food, so they might compete even if they didn't interact directly. Using water or food that individuals of the other species could have used would be scramble competition.

A survey showed that ranchers with cattle on the Henry Mountain range believed that the bison were hurting cattle production by consuming food that cattle could have eaten. They were less concerned about competition for water. They did not think that direct competition—fighting between bison and cattle—was a problem. They did not think that mule deer, jackrabbits, or other herbivores were important competitors. One way to predict whether species compete for a resource is to determine whether they actually use the same resources. All the grazing animals need water, but they may drink it from different sources, or there may be plenty of water for all of the grazing animals.

There are multiple species eating plants on the range, but they may be eating very different plants. Researchers on the shortgrass prairie of Colorado compared the diets of different herbivores, including cattle and bison. Bison specialized on grasses while cattle ate a greater variety of plant types (Figure 13). Each category of plants in the study may include many different species, so the exact amount of overlap is still unknown.

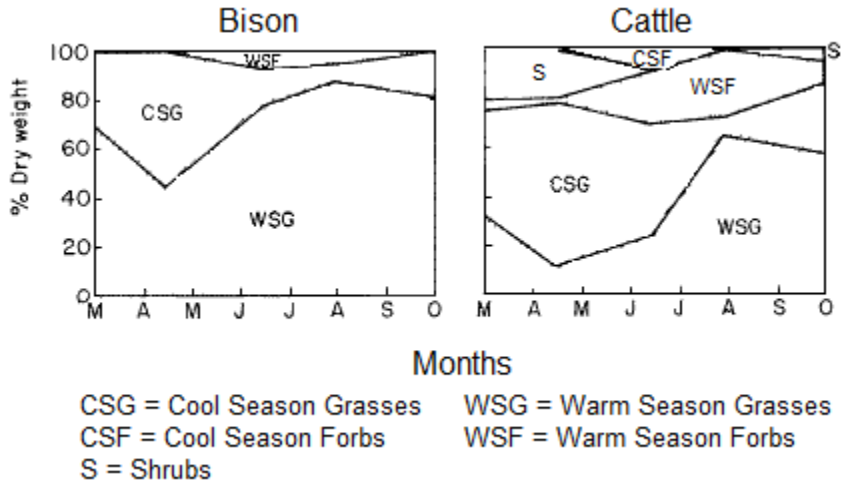



Figure 13. Diets of bison and cattle in northeastern Colorado from March to October. Forbs are plants that are neither grasses nor shrubs. Modified from: Schwartz, C. C., & Ellis, J. E.. (1981). Feeding Ecology and Niche Separation in Some Native and Domestic Ungulates on the Shortgrass Prairie. *Journal of Applied Ecology*,*18*(2), 343–353. http://doi.org/10.2307/2402399.

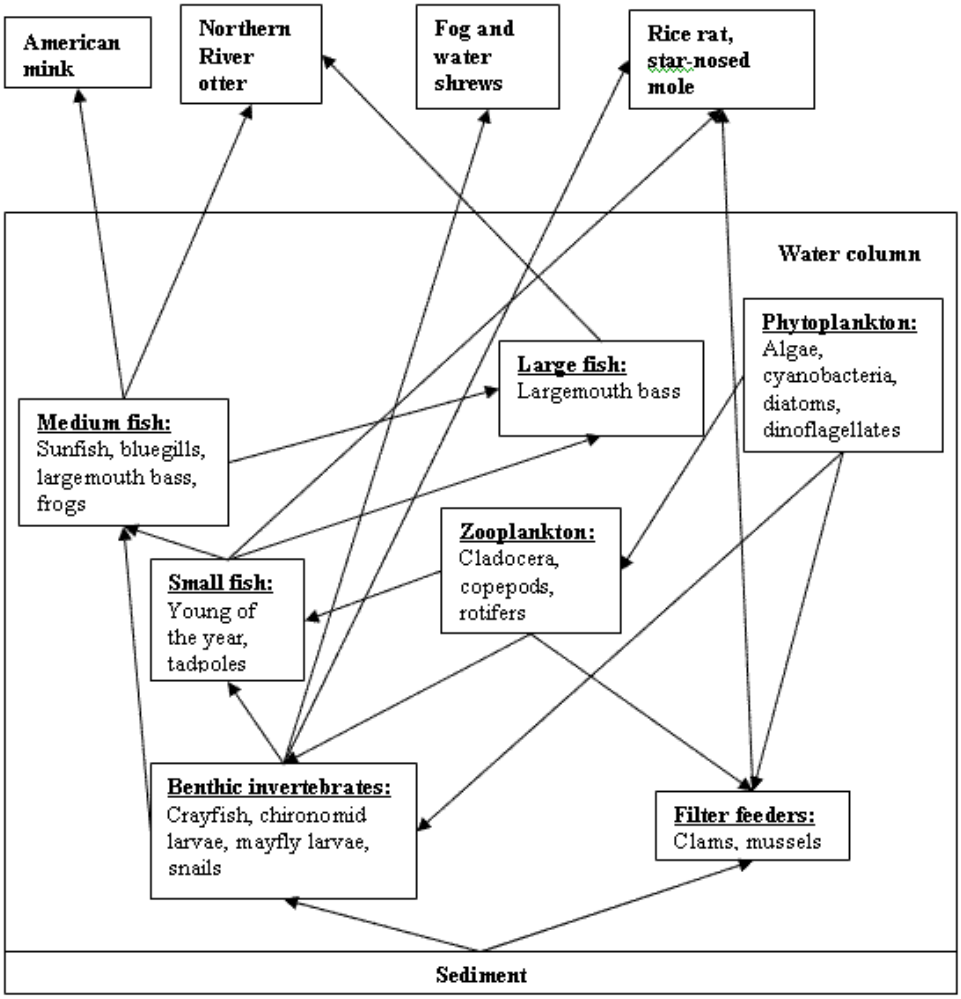
**Analyze the Figure**

- What type of plants made up about 40-80% of the bison diet throughout the study?
- Which animal ate more forbs and shrubs?
- Would a graph that showed proportion of different species (instead of general categories) of plants in the diets probably show more or less overlap?

**Learning from the Case Study**

- Do cattle and bison appear to compete for food?
- How does the information on bison and cattle in Colorado help to answer the question about bison and cattle competition in Utah?
- Could two species use the same resource, but not limit each other's numbers?

As discussed in Chapter 13, food webs can be used to show exploitative interactions but also show or suggest other interactions (Figure 14). For example, otters and mink prey on medium fish, making these species competitors. What other species in this food web might compete, be mutualists, or be commensals?




http://www.epa.gov/oppefed1/models/water/kabam/kabam_user_guide_appendix_d.html

Figure 14. Food web showing many types of interactions in a freshwater ecosystem and the land nearby. Arrows go from the source of energy and nutrients to the consumer of those resources. Species with arrows coming from the same resource are competitors. "Benthic" refers to the bottom of the pond.

**Analyze the Figure**

- What organisms are the producers for this community?
- Which animals are the top predators?
- Which group will have a greater **total** biomass, zooplankton or large fish?

**Check Your Understanding**

- How can food webs show competition?
- What other inferences can be made from food webs?

**Case Study Part 3: What Does the Henry Mountain Food Web Show?**

The Henry Mountain rangeland supports several species (including insects, birds, and mammals) that might eat the same plants that cattle eat (Figure 15). Ranchers consider bison the most important competitor for cattle. Black-tailed jackrabbits are not considered a major competitor. Desert cottontail rabbits are another herbivore that might be competing with cattle. Jackrabbits are not technically rabbits, but they are close relatives. Both rabbits and jackrabbits are classified as lagomorphs. The only other large herbivores in the area are mule deer. Mule deer to not graze on grass like bison and cattle. They browse on other types of plants. Not all species and interactions are represented in the food web. For example, coyotes may be part of the life cycle of certain parasites that infect cattle.

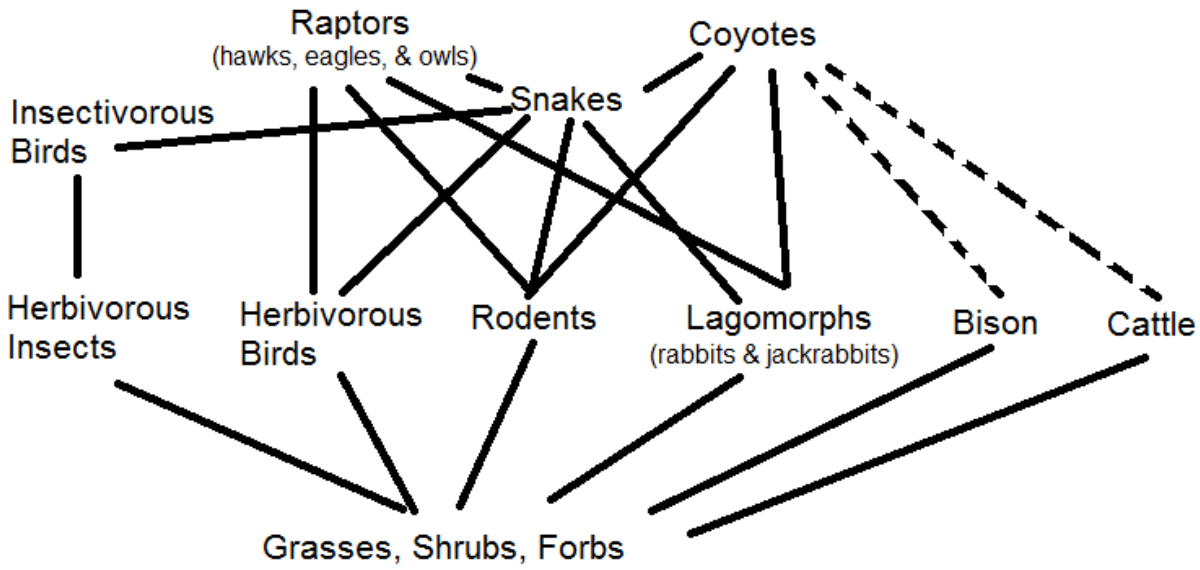



Figure 15. Simplified food web showing some interactions in the Henry Mountain range. Dashed lines represent weak links. A food web that showed all connections would be very complicated and include many more species.

**Analyze the Figure**

- Which species are potential competitors?
- Which animals eat herbivores?
- Which important species or groups of species are missing from the diagram?

Historically, the Henry Mountains probably had more large predators, such as mountain lions, wolves, and bears. Now the largest predators are coyotes. Raptors eat many of the same prey as the coyotes, but coyotes will sometimes eat very young or weak bison and cattle. Coyotes are not much of a threat to healthy adult bison and cattle, even when they hunt in packs. Ranchers in the Henry Mountains (like most ranchers) favor controlling coyotes because they would prefer not to lose any calves to predators.

**Learning from the Case Study**

- What other species compete with cattle and bison for food?
- Could controlling coyotes result in less food for cattle? How?

**Model Skill: Box Plots**

Box plots (also called box and whisker plots) are useful for showing the details of variation in a data set. The box plot shows the **median** (the value that divides the data set in half) and the **quartiles** that divide the data set into quarters.

For example, if you had 16 data points (Table 1), each quartile would contain four of the data points. The median would divide the data so that eight points fell above the line and eight points fell below it. This would be 13.5 for the first column of data because 13.5 is halfway between 13 and 14 (Table 2). What number would divide the data in column two evenly? The first quartile divides the data points so that one quarter is below it and three quarters are above it. The value halfway between 12 and 12.25 is 12.125 (rounded to 12.13), which would be the value for the first quartile for the first column of data. What number would define the first quartile for the second column of data?

Table 1. A hypothetical data set. Values have been put in order from lowest to highest. The bands of shading show the four different quartiles.

| Order | Species A Grown Alone Plant Height (cm) | Species A Grown with Species B Plant Height (cm) |
|---|---|---|
| 1 | 11 | 6 |
| 2 | 11 | 9 |
| 3 | 11.5 | 9.5 |
| 4 | 12 | 9.5 |
| 5 | 12.25 | 9.75 |
| 6 | 12.5 | 10 |
| 7 | 13 | 10 |
| 8 | 13 | 10 |
| 9 | 14 | 10 |
| 10 | 14.5 | 10.5 |
| 11 | 14.5 | 10.5 |
| 12 | 14.5 | 10.5 |
| 13 | 15 | 10.75 |
| 14 | 15.25 | 11 |
| 15 | 15.25 | 11 |
| 16 | 15.25 | 14 |
| **MEAN** | **13.41** | **10.13** |
| **MEDIAN** | **13.5** | **10** |

**Cont.**

**Model Skill: Box Plots, cont.**

Table 2. Values for the quartiles. These are used for creating a box plot.

| | **Alone** | **With B** |
|---|---|---|
| **Minimum** | 11 | 6 |
| **1st Quartile** | 12.13 | 9.63 |
| **Median (2nd Quartile)** | 13.5 | 10 |
| **3rd Quartile** | 14.75 | 10.63 |
| **Maximum** | 15.25 | 14 |

To make a box plot, start by drawing horizontal lines to show the median values for the two categories (Figure 16). The lines for the first quartiles are added below each median and the lines for the third quartile are added above each median. Vertical lines are then added to connect the quartile lines. This forms the "box" that contains half of the data points. The value of the box (Quartile 1 to Quartile 3) is called the **interquartile range**. A larger box—or larger interquartile range—shows that the data vary more.

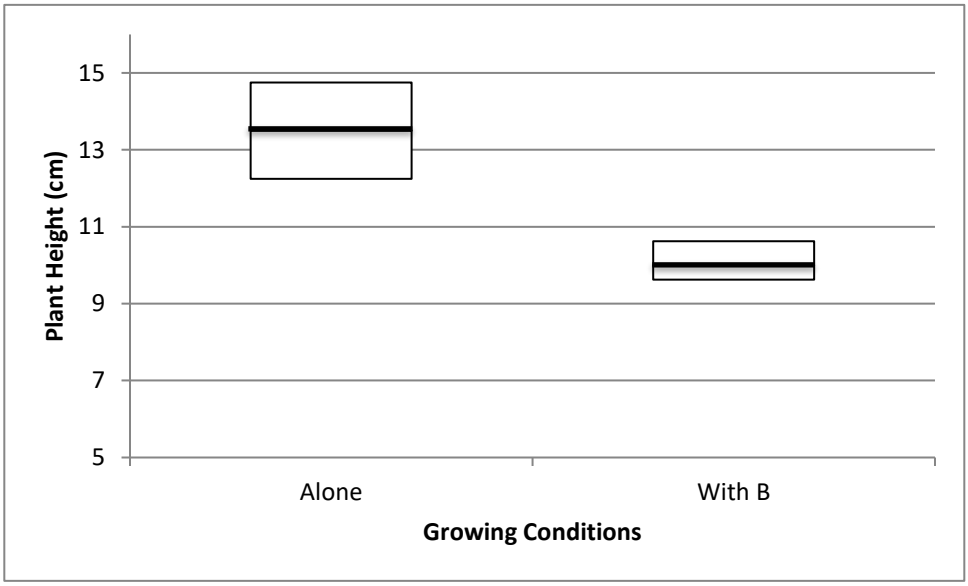



Figure 16. Beginning of a box plot for the data in Table 2. The median values are plotted as horizontal lines and are usually thicker than the other lines. Thinner horizontal lines are added to show the first and third quartiles. Then vertical lines are added to produce the box shape. The distance from the lowest line of the box to the highest is the interquartile range.

**Continued**

**Model Skill: Box Plots, cont.**

Sometimes the maximum and minimum values are used as the ends of the whiskers (Figure 17). These are joined to the boxes with vertical lines. In another method, the ends of the whiskers are 1.5 times the interquartile range above quartile 3 and below quartile 1. When using this method, outliers are shown as separate data points past the whiskers. If a negative value would not be logical, the lower whiskers usually start at zero. For example, there could not be a negative number of species per plot, so the graph would not include negative values and the graph would start at zero.

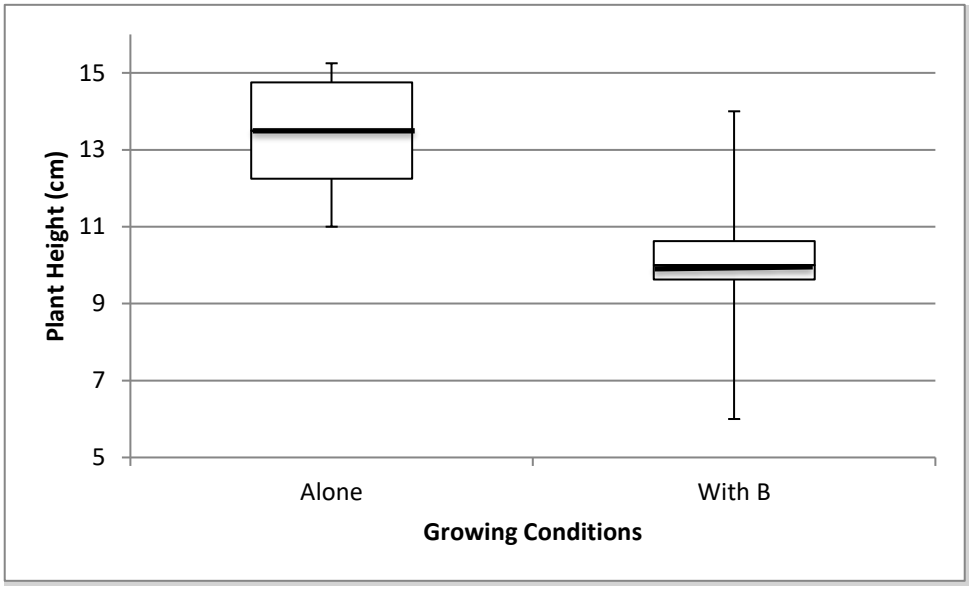



Figure 17. Completed box plot for the data in Table 2. The maximum and minimum are shown as short horizontal lines. Then vertical lines are added to produce the whiskers.

**Analyze the Figure**

- Which growing condition resulted in greater variation in plant height?
- In the plants grown alone, was there more variation below the mean or above the mean?
- Is there overlap in the plant heights?

**Continued**

**Model Skill: Box Plots, cont.**

Notice that the box plot allows more analysis of the variation in the data set. For example, for the plants grown with species B, the variation is not symmetrical. There is more variation in the values within the box above the median. For the plants grown with species B, most of the data is clustered near the mean, but the minimum and maximum values are far from the median. This indicates some extreme values, which are not present in the plants grown alone. Plants grown alone had more variation aside from those extreme values. This detail is not shown in a graph of the mean and standard deviation (Figure 18). Neither of these graphs is incorrect, but each serves a different purpose. If a box plot will be the best way to show your data, see **Taking It Further: Create a Box Plot**.

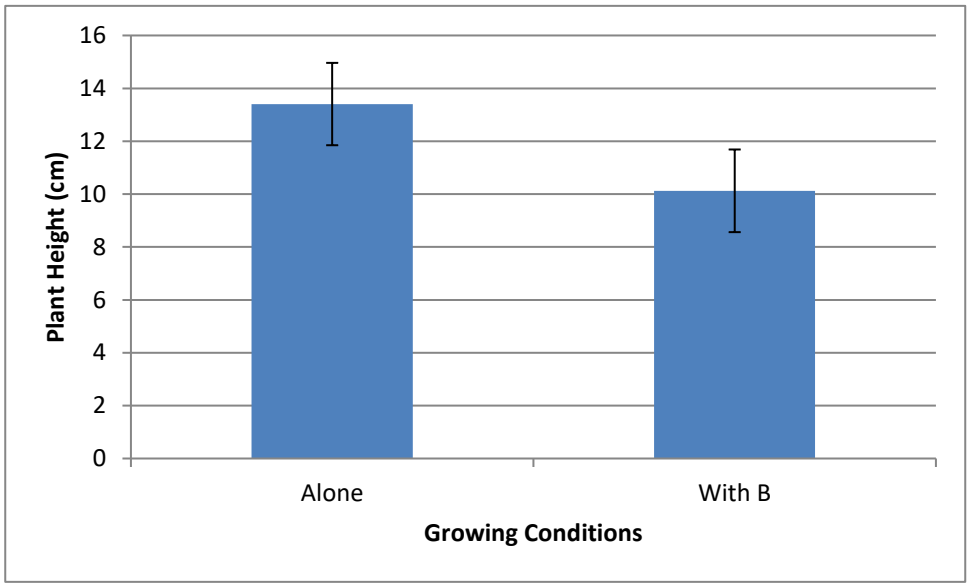



Figure 18. Bar graph (mean +/- standard deviation) for the data in Table 2.

**Analyze the Figure**

- Does the bar graph show which growing condition resulted in greater variation in plant height?
- Does the bar graph show whether, in the plants grown alone, there was more variation below the mean or above the mean?
- Does the bar graph show whether there was overlap in the plant heights?

**Taking It Further: Create a Box Plot**

Table 3. Hypothetical data set.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2 | 3 | 3 | 4 | 5 | 6 | 6 | 7 | 10 |

Start by filling in the values in Table 4. The minimum and maximum values are straightforward. What value is in the middle of the data set so that half the data points are above and half are below (median)? The number that is halfway between the minimum and the median is the value for the first quartile. Because there is an odd number of data points, there is no need to get the average of two numbers. Perform a similar operation to find the third quartile.

Table 4. Values for the data set.

| | **Value** |
|---|---|
| **Minimum** | |
| **1st Quartile** | |
| **Median (2nd Quartile)** | |
| **3rd Quartile** | |
| **Maximum** | |

In Figure 19, use a ruler to draw a horizontal line for the first and second quartiles and the median. The line for the median is usually darker. The lines should all be the same length. Connect the ends of the horizontal lines with vertical lines to make a box. Make short horizontal lines for the maximum and minimum values. These should be centered on the box. Now draw vertical "whisker" lines to connect the extreme values to the box.

Figure 19. Blank for drawing a box plot with the data from Table 4.

**Case Study Part 4: Who is Eating All the Grass?**

To test for competition between cattle, bison, and lagomorphs (jackrabbits and rabbits), researchers created experimental plots at 20 different sites. Each site had three different plots, each plot containing about 6 square meters of potential grazing area. Partial exclosure plots had fences that excluded cattle and bison, but did not exclude the lagomorphs. Full exclosure plots excluded cattle, bison, and lagomorphs. Control plots were the same size as the exclosures but had no fences. All three types of plots were near each other at each site to control for microhabitat differences. The sites were spread out to sample a variety of microhabitats.

To measure how much the herbivores were eating, researchers clipped the grass in the exclosures, took the clippings to the lab, dried and weighed them. They repeated this a year later to measure the above-ground biomass of the plants (see Chapter 5). Grasses are adapted to grazing and fire, so the clipping does not kill the plants. The above-ground grass biomass varied a lot in each treatment but was lowest in the control plots, where no herbivores were excluded (Figure 20, see Model Skill: Box Plots).

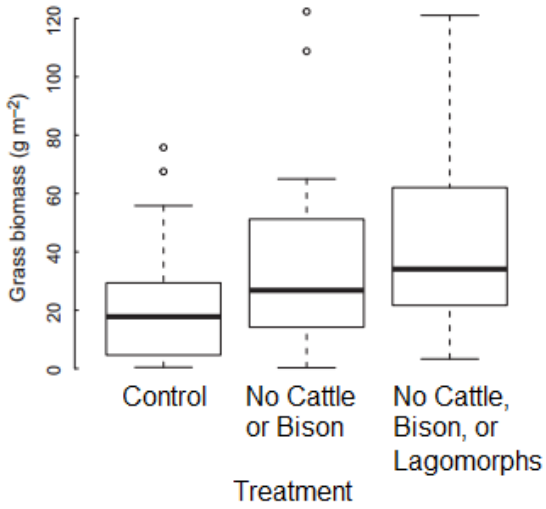



Figure 20. Influence of grazing on production of grass biomass. Control sites did not exclude any animals. Partial exclosures excluded both cattle and bison. Full exclosures excluded bison, cattle, and lagomorphs (rabbits and jackrabbits). Treatments were significantly different from each other. Modified from: Ranglack, D. H., Durham, S., & Toit, J. T. (2015). Competition on the range: science vs. perception in a bison–cattle conflict in the western USA. *Journal of Applied Ecology*, *52*(2), 467-474.

**Analyze the Figure**

- Which treatment had the highest median level of grass biomass?
- Was there overlap in grass biomass for the three treatments?
- Why do you think there was more variation above the median than below it for the exclosure treatments?

To separate the effects of cattle and bison grazing, researchers had to take a different approach. About 10% of the bison had collars that allowed researchers to track them remotely. Helicopter surveys of bison were also used. Researchers calculated bison days in areas (BD) to represent potential bison grazing pressure. For example, 10 bison days could mean either that 10 bison spent 1 day in a location, or that 1 bison spent 10 days in a location. Cattle days (CD) were calculated from rancher reports. There were 21,415 bison days and 81,949 cattle days on the research area during the study period. BD + CD = 103,364, so bison represented about 21% of the total grazing pressure, assuming that one individual of either species exerts the same grazing pressure. Lagomorph grazing could be measured directly by comparing partial exclosures with full exclosures. Overall, 52.3% of the total grazing pressure was due to cattle, 34.1% was due to lagomorphs, and 13.7% was due to bison.

**Learning from the Case Study**

- Which species is competing most with cattle for food in the Henry Mountain area?
- Did the ranchers' ideas about competition match the results of the study?
- What other herbivores on this range could also be eating the same plants as cattle?
- What would make competition higher in some years and lower in others?
- What would you recommend as the best way to improve the Henry Mountain range for cattle? Explain your recommendation.

# Key Concepts

- In commensalism, individuals of one species benefit and there is no cost or benefit to individuals of the other species.
- In mutualism, individuals of both species benefit.
- In interspecific competition, individuals of both species are harmed by the other species, even if one species "wins" the interaction. There is evolutionary pressure for resource partitioning, which reduces competitive exclusion.
- Specific conditions alter interactions between species, such as which competitor "wins," or whether facultative mutualism occurs.
- In any interaction between species, either organism can increase its fitness if it increases benefits and decreases costs. Commensalism could become mutualism or parasitism, for example.

# Apply the Concepts

**Learning Outcomes**

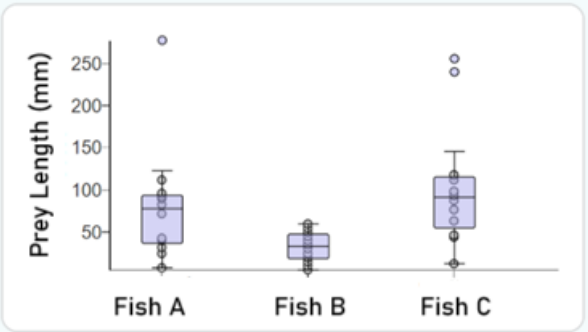
1. *Accurately analyze relationships within and between species*
2. *Make reasonable predictions about how costs and benefits influence species interactions and coevolution*
3. *Draw reasonable conclusions about evolutionary relationships between species*

1. Sea turtles can be messy eaters, leaving algae floating around them as they feed. Small fish often follow the turtles, eating the "leftovers." Identify the costs and benefits of each and characterize the relationship between the sea turtles and fish as competition, mutualism, or commensalism. *(Learning Outcomes 1 & 2)*

2. Are domestic animals (pets, livestock, service animals, etc.) mutualists with humans or are they commensals, competitors, or parasites? Identify the costs and benefits to humans and non-human animals to explain your answer. *(Learning Outcomes 1 & 2)*

3. Several tree species depend on animals to disperse their seeds. These trees often have leaves that turn bright colors when their fruit is ripe, meaning that the seeds are mature and the fruit is highly edible. Explain the steps of coevolution that could have led to this situation. Remember to avoid Lamarckian or teleological explanations. *(Learning Outcomes 2 and 3)*

4. Fish eat a variety of freshwater invertebrates. Imagine a study that compared the size of prey consumed by 3 different fish species (Figure 21; *Learning Outcome 1*).




Modified from: https://www.cdc.gov/cove/data-visualization-types/box-and-whiskers-plot.html

Figure 21. Hypothetical prey size of three fish species. The line in the center is the median. The box is the interquartile range.

A. Which species has the greatest variation in food size?
B. For fish species A, is there more variation above the median or below it?
C. Does there appear to be a lot of intraspecific competition between the different species? Explain your answer, using evidence.
D. Would you expect more competition between individuals of species B or between species B and C? *(Learning Outcomes 1 & 2)*

5. Scientists in Kenya wanted to know whether large wild ungulates (giraffes and elephants) or medium wild ungulates (zebras, African buffalo, or various antelope) competed for food with domestic cattle on the tropical savanna. They measured multiple variables on plots where either large wild ungulates or both medium and large wild ungulates were excluded, but cattle were present. Researchers predicted that competition might be more severe during the dry season, when food tends to be limited. An alternative hypothesis was that zebras might help cattle, both by removing dead grass that interferes with cattle reaching their preferred food, and by stimulating grass to sprout new leaves. The measure that concerns cattle owners most is probably the weight gain of the cattle (Figure 22).

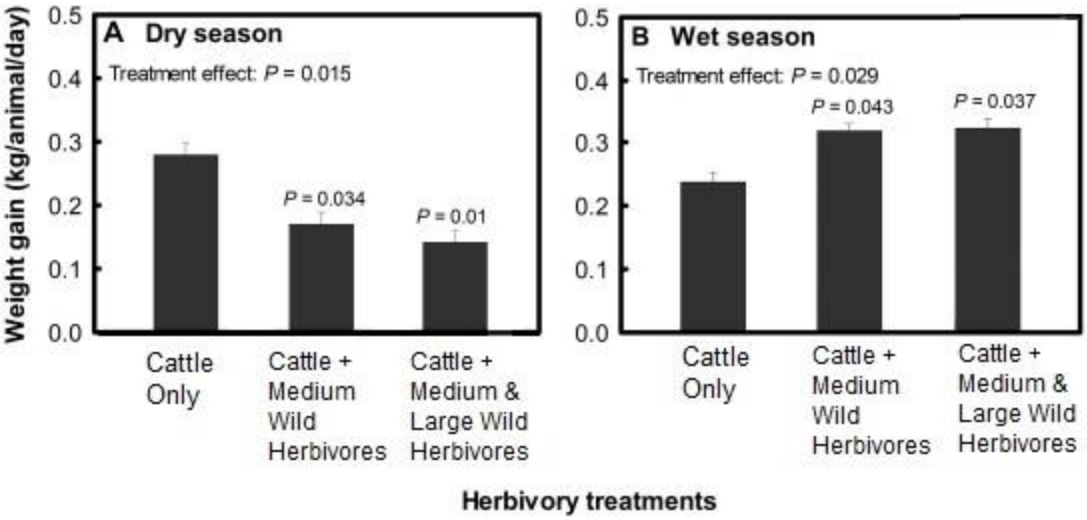



Figure 22. Mean +/- standard error of weight gain in cattle in Kenya under different grazing conditions and in different seasons. The P-value for the treatment effect for each season refers to the overall difference between grazing treatments. P-values over individual bars are comparisons with the cattle-only treatment for that season. Adapted from: Odadi, W. O., Karachi, M. K., Abdulrazak, S. A., & Young, T. P. (2011). African wild ungulates compete with or facilitate cattle depending on season. *Science*, *333*(6050), 1753-1755.

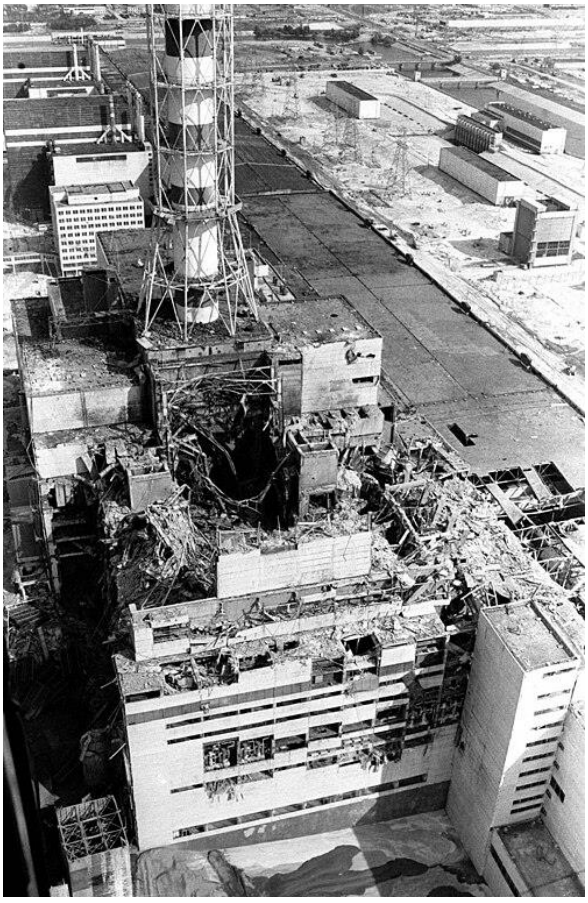
A. In the dry season, did medium wild herbivores appear to compete with cattle for food? Provide evidence to support your answer.
B. In the dry season, did large wild herbivores appear to compete with cattle for food? Provide evidence to support your answer.
C. Is the pattern the same in the wet season as in the dry season? Provide evidence to support your answer.
D. Why might there be seasonal differences in competition? *(Learning Outcomes 1 & 2)*

**Unit V: Communities**

# Chapter 16: Changes in Communities

## Case Study Part 1: An Unprecedented Disaster

April 25th, 1986 was a normal day in the city of Pripyat in the Soviet Union (now Ukraine). People attended school, worked, gardened, or fished. During a system test at the nearby Chernobyl Atomic Power Plant (CAPP) that night, something went horribly wrong. By the early morning hours of April 26th, fire and explosions had led to the largest radiation leak the world had ever seen (Figure 1). Mass evacuations were ordered on the afternoon of April 27th. Eventually, over 100,000 people were permanently evacuated from an exclusion zone in a roughly 30 km radius of the damaged reactor.



https://commons.wikimedia.org/wiki/File:IAEA_02790015_%285613115146%29.jpg

Figure 1. Reactor at the Chernobyl Atomic Power Plant after the explosion that caused a massive release of radiation.

Winds spread radioactivity throughout the region and into Europe. Rivers and other surface water sources were contaminated. Animals died or became sick. A 4-km square area of Scotch pine forest turned red-brown and died (this would be known as the red forest). By December a concrete "sarcophagus" had been built over the damaged reactor to contain the remains, though other reactors in the CAPP complex were in use until 2000. The exclusion zone will be contaminated with radiation for thousands of years.

Once the immediate crisis had passed, people began speculating on the fate of the exclusion zone. Would it become a nuclear wasteland, devoid of life? Would it be taken over by horribly mutated plants and animals, or would it return to the natural communities that pre-dated the modern city? This chapter will explore how communities respond to disturbances, both large and small.

**Learning from the Case Study**

- How might a disaster caused by radiation have different results than a flood or fire?
- How might the recolonization of a city be different from the recolonization of a more natural area?

# Learning Outcomes

1. *Accurately describe and explain the effects of different disturbances on communities.*
2. *Make and defend reasonable predictions about community changes following disturbances.*
3. *Accurately relate characteristics of species to successional changes in communities.*
4. *Relate successional stages to climate and other environmental conditions.*

**Vocabulary Toolkit**

**Word Watch List**

**Disturbance:** Unpredictable events that cause major changes in communities
**Primary succession:** Series of fairly predictable changes in communities after a disturbance that removes the soil
**Secondary succession**: Series of fairly predictable changes in communities after a disturbance that leaves the soil intact
**Competitor species**: Later colonizers that can out-compete other species
**Stress tolerators**: Species that can grow in stressful conditions, such as shade
**Pioneer species**: Early colonizers that invest heavily in reproduction
**Forbs**: Non-woody plants that are not grasses or similar plants. Also called herbs
**Climax community**: Community that is only replaced after a disturbance
**Carbon sink**: Systems that remove and store atmospheric carbon
**Sediment:** Soil that was carried by water and deposited somewhere else
**Facilitation**: Model in which pioneers improve habitat for later species
**Tolerance**: Model in which species that are adapted for extremes of specific conditions persist in a community
**Inhibition**: Model in which earlier species prevent success of later species
**Stability**: Ability of a community to persist after disturbance
**Resistance**: Ability of a community to retain the same species after disturbance
**Resilience**: Ability of a community to quickly regain the same species after disturbance
**Functionally equivalent community**: Community consisting of species with niches similar to those of the community it replaced. It has similar patterns of productivity and diversity
**Positive correlation**: Relationship between variables that increase or decrease together
**Negative correlation**: Relationship between variables that change in opposite directions
**Interpolation**: Prediction of the value of a variable between known values
**Extrapolation**: Prediction of the value of a variable beyond known values

## Disturbances Change Communities

A fire sweeps through a grassland, burning all the dry fuel in its way. The next day the landscape is black and barren with no visible life. It is easy to see this as the death of a community, but it is really the start of a different phase. A few days later, a green haze will show new grass shoots sprouting from roots that were protected by soil. Some plants will grow rapidly in the new environment (Figure 2) and others will successfully invade the burned landscape. In a year or two, the grassland may look just as it did before the fire. If many years pass without another fire, the grassland may turn into shrubland or forest. Fires are a kind of ecological **disturbance**. Disturbances are events that quickly and significantly change communities. While fires can be deadly and destructive, fire also maintains many ecological communities. Some plants only sprout after fires. Some communities disappear without fire.

https://parks.sonomacounty.ca.gov/learn/blog/seeds-and-squirrels-natures-approach-to-fire-recovery

Figure 2. Regrowth of grass after a fire.

Abiotic disturbances include fires, floods, volcanic eruptions, major storms, glaciers, and landslides. Heavy damage caused by diseases, grazing, human actions, and other biological activity are also forms of disturbance. Disturbances may be large or small, minor or severe. Disturbances are unpredictable. The species living in inter-tidal zones have predictable changes in tide level, air temperature, and precipitation. These are not considered disturbances. A major storm that scrapes the community off the rocks is a disturbance.

The process of change in a community after a disturbance is called **succession**. In terrestrial communities, soil is critical to recovering from a disturbance. When no soil is present, the changes after disturbance are called **primary succession**. Volcanic ash or lava may bury soil under deep layers of rock. Flood waters or glaciers may scrape soil away (Figure 3).

http://www.nps.gov/kefj/learn/nature/plant-succession.htm--Kay White

Figure 3. Example of primary succession in Kenai National Park, Alaska. As the glacier melts, it exposes bare gravel without soil.

Successional stages after a disturbance that removes soil are usually very slow. Lichen may start to colonize bare rocks (Figure 4), but little else can grow without soil. With little organic matter and poor conditions for bacteria, not much soil will be made either. If the site is wet enough, mosses may colonize the rocks, but they do not survive well in dry or sunny conditions. If soil is deposited on the site by wind or water, the recolonization process will happen faster.

http://commons.wikimedia.org/wiki/File:Lichen_DSC00612.JPG

Figure 4. Lichens growing on a rock. Lichens are a mutualism between fungi and algae and can grow without soil. They are usually less than 1 cm tall.

When soil is present, the changes after a disturbance are called **secondary succession**. Fires, storms, and many other disturbances leave the soil behind. Secondary succession is much more common because most disturbances do not remove soil. Plant growth can begin immediately in secondary succession because seeds, roots, and other reproductive structures may already be in the soil. Bacteria and fungi that support plant growth may also be present.

Traits useful for success in one stage of succession are often a problem at a different stage. Leaves that are effective in sunny open areas may not be effective in a crowded forest. Seedlings that grow in damp shady places might die in sunny open places. Plants that invest resources in toxins that kill competitors might need better soil than is present in early successional stages. The Grime C-S-R model (Figure 5) explains plant succession as the result of evolution of resource allocation. While these patterns are called strategies, this does not imply that plants are making choices. Plants can be described by their ability to out-compete other species (**Competitors**), grow in extreme environments (**Stress tolerators**), or colonize an area after disturbance (Ruderals or **pioneers**). A plant has limited energy and nutrients to invest in reproduction, support structures, or ways to tolerate harsh environments. If it invests more in one strategy, it must invest less in the others. Some plants fit neatly into one of the three categories, while others will have some characteristics of two or three of these categories. For example, they may alter their growth forms in response to their environment (a C trait) but also grow slowly (an S trait).

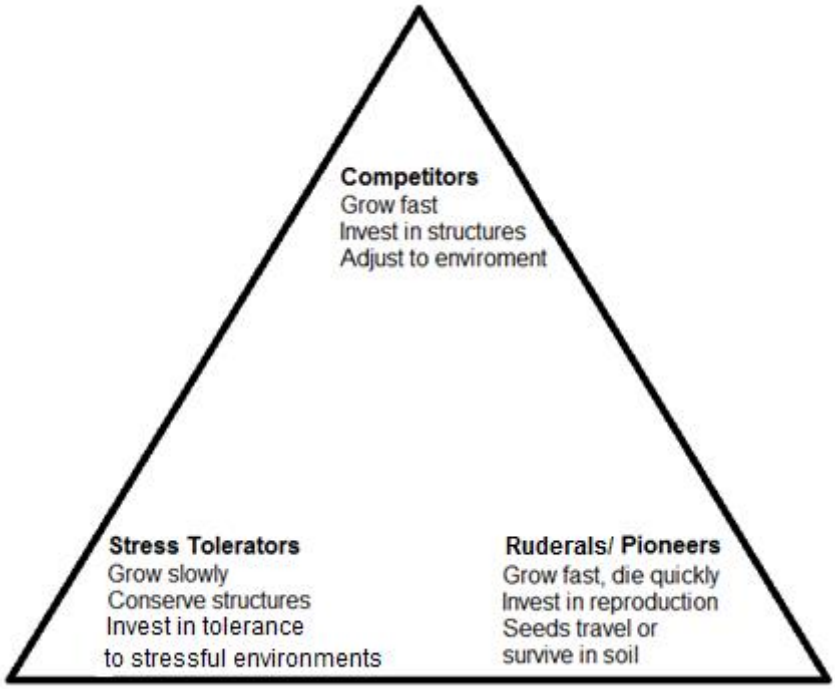



Figure 5. Three different types of plant life history strategies. Some plants fall into one of the extremes, while others use a combination of strategies. Based on Grime, J.P. (1977). Evidence for the Existence of Three Primary Strategies in Plants and Its Relevance to Ecological and Evolutionary Theory. *The American Naturalist*, 111: 1169-1194.

**Analyze the Figure**

- Which of the categories would best describe a plant that takes very different shapes when it is grown under different conditions?
- Which of the categories reflects K-selected life history strategies?
- Would it be possible for a plant to have different strategies at different stages of its life? Explain your answer.

The patterns of succession after specific disturbances are fairly predictable in a given biome. The actual species will vary from place to place, but some general patterns are expected. For example, the stages of secondary succession are described for many temperate forest biomes (Figure 6). The first species to grow on exposed soil will be ruderals or pioneer species. These are often **forbs**, which do not invest in woody tissue. They are often strongly r-selected (see Chapter 13). They grow fast, produce many seeds, and die young. Most will be annual plants, meaning that they only live for one season. They do not invest in large root systems or woody stems. Almost all their energy goes into reproduction. They are adapted to living in full sunlight in thin soil. Their seeds are usually adapted to move long distances and survive a long time in the soil. This allows them to colonize areas opened by disturbances.

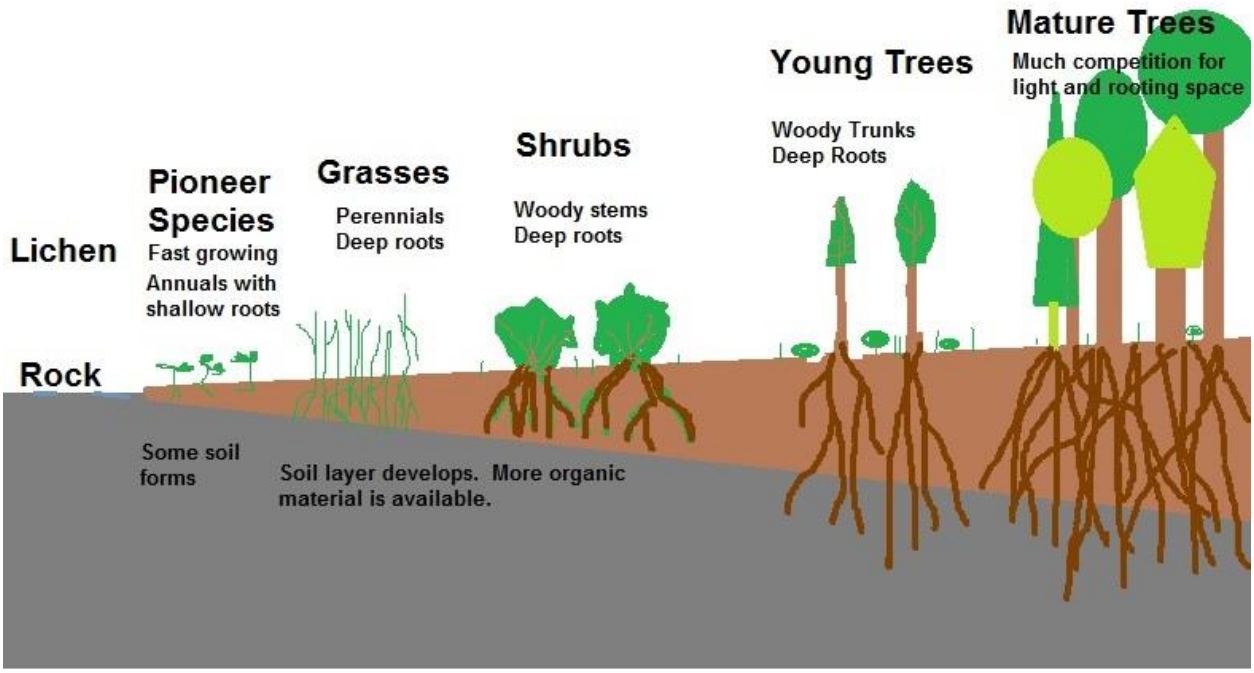



Figure 6. Stages of succession in a temperate forest. If succession starts with bare rock, it is primary succession. If soil (shown in brown in the figure) is present, it is secondary succession.

**Analyze the Figure**

- Which stages of this time series might have a high productivity? Explain your answer.
- Which stage probably has mostly r-selected species? Explain your answer.
- Do you think that all of the stages will last an equal amount of time? Why or why not?

As years pass, grasses and other plants will start to colonize the site. These plants are usually perennials, meaning that they do not need to grow from seeds every year. Their roots survive even in harsh winters. They do not grow upwards as fast in their first year as the weedy species did because they are investing in roots underground. In seasonal climates, the root systems allow them to grow faster in the spring than annual plants do because they have stored energy and water and already have a system for getting more. These competitor species will start to out-compete the pioneers by growing faster, leaving the pioneers in the shade. Later-successional species are generally more K-selected than earlier successional species.

Shrubs make long term investments both below ground and above ground. They have woody stems that give them an advantage in the spring. While the grass is still growing up from roots, the bushes only have to produce leaves, which then capture the sunlight, leaving grasses and herbs in the shade. These bushes may have started to grow years earlier, but they grow slowly while they are investing in making the wood in their stems and roots. Shade is an important source of stress. Other sources of stress are limited nutrients and conditions that are extreme in terms of temperature, pH, moisture, or toxins. Stress-tolerant species specialized for surviving these conditions will be at an advantage in these conditions.

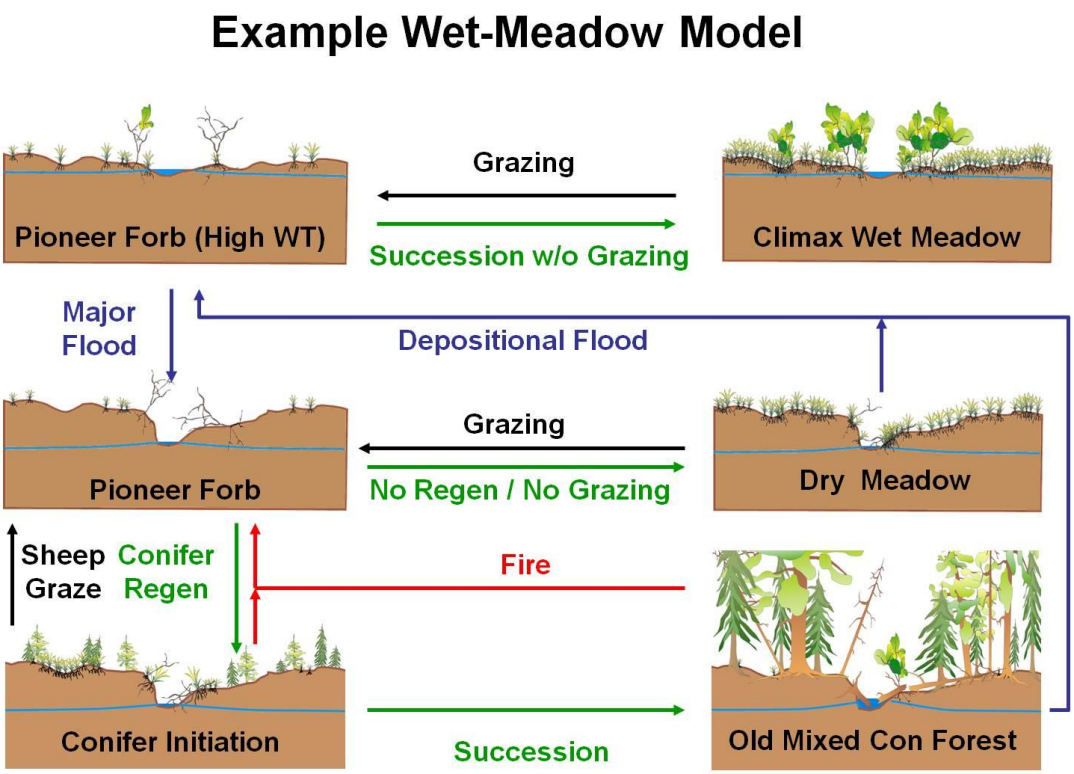
As the years go by, trees that were growing in the shade of shrubs will grow past their competitors and will start to dominate the site. Their long-term investment in trunks allows them to get sunlight before it hits the shrubs. Different tree species may out-compete each other, so the type of dominant trees may change over time as well. The type of species that remain dominant are the **climax community**. At any stage, another disturbance can reset the community to an earlier successional stage. The same species may be present for a long time before or after they are the dominant species. A maple tree may sprout when the dominant species are grasses and herbs. Grasses and herbs may grow in the mature forest. They are just not the dominant species.

During these transitions, several attributes of communities can change. If the climax community is dominated by trees, the total above-ground biomass of the community may be highest at that stage. The trees can be a **carbon sink**, removing carbon dioxide from the atmosphere during photosynthesis and storing it in their tissues. Belowground biomass may be even higher in a grassland. The total productivity of a climax community may be lower than the productivity of earlier stages because only a fraction of a tree's cells are capable of photosynthesis. Increasing shade means less light available for photosynthesis. Changes in species diversity during succession will be discussed in Chapter 17.

**Misconception Alert: Climax communities are the most advanced successional stages.**

**FALSE**. None of the stages or species are more “advanced” than the others, they are just adapted for success under different conditions. A landscape that includes a mosaic of successional stages will often the greatest diversity of species.

The type, timing, and frequency of disturbance are also important in determining the outcome of succession. A fire in an established grassland will probably not kill the grass, but a prolonged drought might. In the example of a wet meadow, possible disturbances include grazing, fire, and flooding (Figure 7). A meadow with a high water table is usually colonized by pioneer forbs. If it is not grazed, burned, or flooded, it will eventually become a wet meadow. Grazing without flooding or burning will keep it a pioneer forb community. A major flood will erode the area. The water table will be lower, because fine **sediments** that trapped water near the surface will be flushed away. Forbs will start to invade again. If there is no grazing or fire, the area will become a dry meadow. If there is enough grazing, it will remain a pioneer forb community. If conifers start to grow in the area, and there is little grazing, the area may become a conifer forest. Fire in the young or old conifer forest can make the area a pioneer forb community again. If either the old forest or the dry meadow is flooded with slower water that deposits new sediment, the area will be back to a pioneer forb community with a high water table. There is no predictable path to a final community. There are just fairly predictable changes that follow specific types and sizes of disturbances that occur at specific frequencies.




http://www.fs.fed.us/pnw/lwm/aem/images/wet_meadow.jpg

Figure 7. Effects of different disturbances on wet-meadow succession. Forbs are non-woody plants other than grasses. “High WT” is short for high water table. “Regen” is short for regeneration. “Con” is short for conifer. The blue line shows the depth of the water table. Fire, grazing, and flooding all determine what the climax community will be.

**Analyze the Figure**

- If a dry meadow is heavily grazed, what does the model predict for the next successional stage?
- Why might the type of disturbance (fire or flood) in an old mixed conifer forest lead to a different community in the successional stage?
- Identify the possible climax communities. How did you determine they were climax communities?

**Check Your Understanding**

- Describe some types of disturbance and how they might influence a community.
- Explain why different types of plants might dominate the community at different times.
- Why might forest fires result in higher levels of atmospheric carbon?

**Successional Stages Vary Across Biomes and Microclimates**

Succession changes are specific to locations and conditions (Table 1). If an avalanche removes all the trees on the slope of a mountain, the stages of succession will be different from the expected stages following a severe windstorm in a tropical forest. Local climate and soil conditions influence possible successional stages. A rocky area in the mountains may never have any community other than lichens. Even within the same biome, the species may vary between locations that vary in microclimate, soil conditions, or other factors.

Table 1. Dominant plant types in the stages of secondary ecological succession in selected biomes. Even within biomes, the stages will differ due to smaller-scale differences in conditions.

| | **General Secondary Successional Stages** | | | | |
|---|---|---|---|---|---|
| **Biome** | **Early** | | **Middle** | | **Climax** |
| **Desert** | Annual Plants | | Shrubs | | Cacti and Shrubs |
| **Deciduous Forest** | Annual Plants | Grasses & Forbs | Shrubs | Pioneer Trees | Deciduous Trees |
| **Tundra** | Lichens | | Mosses & Shrubs | | |
| **Grassland** | Grasses & Forbs | | | | |
| **Rainforest** | Annual Plants & Forbs | | Pioneer Trees | | Climax Trees |

Small-scale patterns result in a patchwork of species in the larger plant community. A grassland may never become a forest if the area is too dry. Microclimates near water in the same grassland may support tree and shrub growth. These areas are called gallery forests because the look like long hallways (Figure 8). North-facing slopes may have a different climax community than south-facing slopes due to differences in moisture and temperature. Substrates can also influence succession. For example, the African savannahs have few trees because of the hard mineral "pan" below the soil, which excludes most tree roots. Where the pan is broken, trees can invade. Distribution of nutrients in soil can also influence succession.

http://www.riley.army.mil/News/ArticleDisplay/tabid/98/Article/611926/tallgrass-prairie-national-preserve-the-last-stand.aspx

Figure 8. Gallery Forest in the Tallgrass Prairie National Preserve in the Flint Hills of Kansas, USA.

**Analyze the Figure**

- What type of plants seem to cover most of the area?
- What might cause the pattern of tree growth? (Hint: the trees are growing in low places.)

Biomes and microclimates will also influence the rate of succession. Areas with warmer, wetter climates can make soil much faster than colder, drier regions. They will have greater productivity and decomposition. This is particularly important in primary succession. Any areas where species can survive will probably have unique successional patterns. For a discussion of one way that succession can happen in our own bodies, see **Make the Medical Connection: Microbial Succession in the Human Gut**.

**Make the Medical Connection: Microbial Succession in the Human Gut**

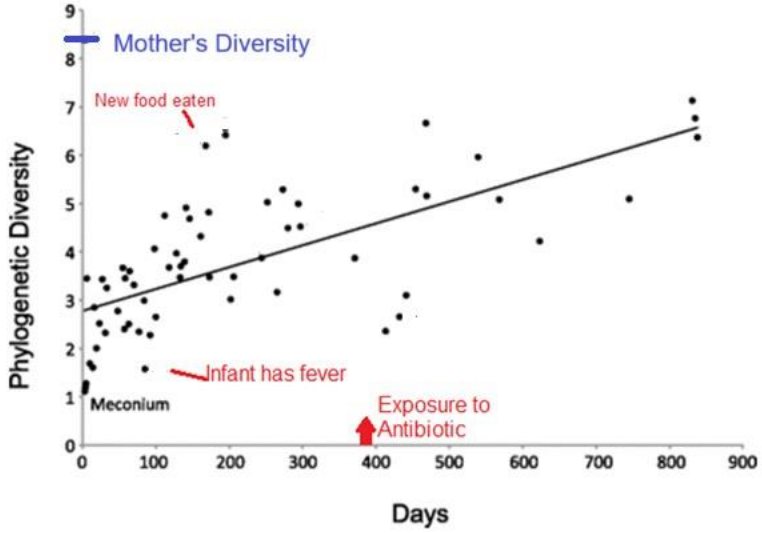



Figure 9. Diversity of microbes in the gut of one human in the days after birth. Meconium is stool produced directly after birth. Modified from: Koenig, J. E., Spor, A., Scalfone, N., Fricker, A. D., Stombaugh, J., Knight, R., ... & Ley, R. E. (2011). Succession of microbial consortia in the developing infant gut microbiome. *Proceedings of the National Academy of Sciences*,*108*(Supplement 1), 4578-4585.

**Analyze the Figure**

- What is the overall pattern of diversity in the infant gut community?
- What events might cause exceptions to the general pattern?

Before birth, our bodies are empty landscapes, not yet colonized by microbes. Pioneers arrive at birth. Only some can establish colonies. Gut communities go through successional changes as their resources change. In the beginning, bacteria that use milk sugar and proteins dominate. These communities become more diverse as new pioneers arrive. In time, bacteria that thrive on starches and other types of food take over. Eventually, the toddler begins eating table food. The bacterial community changes again, becoming more diverse. It takes years for the diversity of a newborn's gut microbial community to develop the diverse community found in the adult gut (Figure 9).

Many researchers now study the effects of antibiotic use, feeding method, and delivery method on the successional stages, and how this influences the health of the child.

**Case Study Part 2: Return to Pripyat**

At the time of the CAPP accident, most of the area that would become the exclusion zone was urban, agricultural, and forest. There were also wetlands and aquatic areas. The forest trees were about 2/3 conifers (such as pines and firs) and 1/3 deciduous (such as birches, aspens, alders and oaks). The conifers of the red forest took most of the damage from the radioactive materials because their needles acted as filters for contaminated airborne particles. The surviving trees were often abnormal. The hardwood trees also had some damage and abnormal growth, but most survived.

Background radiation levels are still well above normal in the exclusion zone, but there is little immediate risk to people visiting the site. The exclusion zone is now a tourist destination. Scientists have also returned to the region to see how organisms have responded to the radiation and the departure of almost all humans. Instead of a nuclear wasteland, the researchers found thriving non-human communities. Soon after the accident, the standing dead trees of the red forest were cut down and buried. The soil was turned over by bulldozers to contain radioactivity. Pine seedlings were planted, but most of these died. By 1994, the red forest had become a grassland. Twenty-five years after the accident, Scotch pines had begun reclaiming the red forest.

Changes in the urban areas were dramatic. Before the evacuation, humans maintained concrete and asphalt. They mowed some areas and used herbicides. Without regular maintenance, even concrete did not prevent trees and other plants from recolonizing the city (Figure 10).

**Do Try this at Home: Microbial Succession**
Take a slice of bread and moisten it with a wet cloth or spray of water. Leave it exposed to the air for a day so that it can pick up mold spores. Seal the bread inside of a zip-top bag, then inside another bag. As the days pass, watch as the fungal communities change. You can map them by laying a grid on a clear sheet of plastic (such as a report cover) over the bread. Note the color and texture of the mold, as well as the area it covers. Food source, temperature, and humidity will potentially influence your microbial community. Which species colonize first? Do these get overgrown by later species? What happens to diversity over time?

Do not open the bags**.** Mold spores can be toxic or cause allergic reactions. At the end of the experiment, dispose of the sealed bags and bread safely in an outdoor trash container.

https://commons.wikimedia.org/wiki/File:Chernobyl_Reactor_5_-_Chernobyl_Exclusion_Zone_-_Northern_Ukraine_%2827066575966%29.jpg

Figure 10. Chernobyl Reactor 5 in 2016.

The city of Pripyat was built in the 1970s to support the CAPP. Planners used several principles of good urban design, including providing green spaces. Pripyat had many ornamental trees along streets and in groves. Pripyat was also surrounded by forest. This decreased the distance between open areas and existing trees. The urban areas were also relatively young, so there may have been viable forest seeds in the urban soil.

To understand plant succession in Pripyat, researchers mapped the locations of pre-evacuation trees, then measured later growth. They hypothesized that the composition of the present successional stage would depend on which trees were present before the accident, which trees could colonize urban sites, and which trees could withstand shade as trees became crowded. Their findings supported this hypothesis (Figure 11).

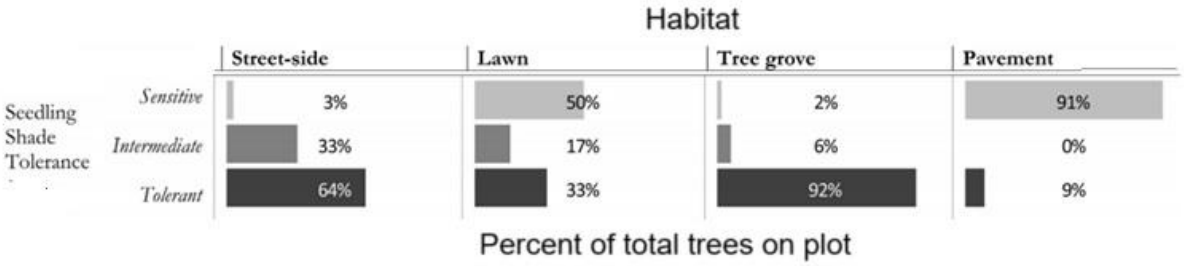



Figure 11. Percent of trees with varying degrees of shade tolerance in different habitats of Pripyat, Ukraine. Modified from: Laćan, I., McBride, J. R., & De Witt, D. (2015). Urban forest condition and succession in the abandoned city of Pripyat, near Chernobyl, Ukraine. *Urban Forestry & Urban Greening*, *14*(4), 1068-1078.

**Analyze the Figure**

- Which of the 4 habitat types have the greatest percentage of shade-sensitive seedlings?
- Which types of trees (shade sensitivity) were most common in the tree grove sites?

Street sides contained mature trees of several species at the time of the evacuation. These trees were a seed source for seedlings. The tree density was high in this habitat, so only seedlings with some shade tolerance survived under the canopy of mature trees. Horse chestnut trees never regenerated in Pripyat.

Seeds of many kinds could be carried or blown onto lawns. Early colonists of the lawns might be very sensitive to shade. As the lawns filled in with trees, these shade-sensitive trees gradually started dying off, while more shade-tolerant seedlings could grow in their place.

Norway maple trees were very successful at reproducing in areas that had been ornamental tree groves. The mature trees acted as seed sources. These areas also had very high tree densities. Maple seedlings are very shade-tolerant and survived in these shady areas.

Some trees—such as poplars and aspens—reproduce asexually by sprouting new trunks from specialized roots. These clones can be very effective colonizers because the mature trees provide resources for the new sprouts. In every location where there were pre-evacuation poplar trees, new poplars had spread through cracks in the pavement or in debris piles on top of the pavement. Aspens were also common in pavement habitat. Poplar and aspen seedlings are vulnerable to shading by other species, but few other species can establish themselves in pavement habitats, so interspecific competition is low.

As the exclusion zone reverted to grassland and forest, it provided habitat for wildlife with no hunting, trapping, or competition from livestock. It is now forbidden to take anything from the exclusion zone, including game animals, because of contamination. The exclusion zone has become a reserve that is home to many species, including large mammals that are rare elsewhere, such as wolves, brown bears, and lynx. Endangered Przewalski's horses were even introduced to the area.

**Learning from the Case Study**

- Were changes in the exclusion zone more like primary or secondary succession? Explain your answer.
- Which changes probably came first, vegetation changes or changes in animal life? Explain your answer.
- What factors led to success of individual tree species in the exclusion area?

**Check Your Understanding**

- Will the climax species be the same in all biomes?
- How might microclimates and patchy soil conditions influence successional stages?
- What conditions might make successional changes happen faster?

**Interspecific Relationships Influence Successional Changes**

One model for explaining succession is **facilitation**. Pioneer species can change the environment in ways that allow later stages to thrive. For example, the organic material from pioneer species may enrich the soil. This enrichment may help the pioneer species as well as later successional species. The roots of earlier stages may break up the soil, making it easier for both pioneers and later plants to grow their roots. In time this will increase competition. In a hot environment, the shade of "nurse trees" provides a cooler, moister environment for new plant growth. The plants growing in its shade may have no effect on the nurse tree when they are few or small. Eventually, they may increase competition for water or nutrients. In the case study, aspens and poplars helped to break up hard surfaces. This would allow other plants to invade the area. For more on this topic, see **Testing Hypotheses: Do transplants facilitate dune plant growth?**

**Tolerance** of environmental conditions is also a model for understanding successional changes. As pioneers and later stage species change the environment, conditions may become more challenging for pioneering species. As shown in the case study, seedlings of many early successional species grow well in full sun, but not in shade. Shade-sensitive pioneer species may be unable to survive their seedling stage when other trees block sunlight. When the adult pioneers die, they will be replaced by shade-tolerant later successional species. Eventually, only species that can tolerate shade (or other relevant stress) will dominate the community.

The **inhibition** model explains succession as the result of competition between plants of all stages. For example, plants can make conditions stressful for their competitors by making the soil more acidic or toxic, or by competing for sunlight, water, and nutrients. Inhibition excludes both earlier and later successional species. If some species are effective at inhibition, they will remain the dominant species until disturbances allow other species to invade. For example, some conifers lower the pH of the soil. Other species may not have adaptations that allow them to live in areas where these conifers have dominated long enough to change the soil pH. The key difference between the inhibition and tolerance models is that tolerance assumes that only later successional species are influenced, while inhibition prevents both earlier and later successional species from establishing themselves.

Table 2. Comparison of three models of causes of succession. All can operate in the same community at the same time.

| Model | Example | Effect on Earlier Stage Species | Effect on Later Stage Species |
|---|---|---|---|
| **Facilitation** | Increased soil quality | Positive or Neutral | Positive |
| **Tolerance** | Shading | Negative | Positive |
| **Inhibition** | Toxins | Negative | Negative |

All these models may explain the changes happening in the same community. Which individual colonizes a specific spot may be due to a combination of facilitation, inhibition, and tolerance

effects. Random events can also influence which plants grow in a particular place and time. For example, there are many ways a seed may happen to be in an area when the site becomes available for new plant growth. Parts of clonally reproducing plants may also remain in the soil after the parent plant is gone.

While plant species are the most obvious dominant species in terrestrial communities, species from all kingdoms perform important roles. For example, the fungi and algae in lichens may be the first multicellular pioneers, especially in primary succession. Decomposers from all kingdoms influence the community by recycling nutrients and building soil. Animals may be important in grazing or carrying seeds or spores to disturbed areas. The animals in each community will also add organic material and may consume pioneer or competitor plants that are not well defended.

Plant successional stages can drive biodiversity. For example, a fungus may only grow well in the shade of a mature forest. An animal may be very successful in the open area of a middle successional stage, but not in later stages when trees fill in the area. Some species require patches of habitat that are in different successional stages.

**Testing Hypotheses: Do transplants facilitate dune plant growth?**

Coastal sand dune communities are prone to small and large disturbances. Wind off the water can deposit salt, blow the sand into new shapes, uproot some plants, and bury others. Dead material tends to blow away, so it is not available to retain moisture or nutrients. Water also drains quickly due to sand's large, irregular grains. In moist soils elsewhere, the high thermal inertia of water dampens temperature fluctuations. Daytime temperatures in dry sand can be very high, as many a barefoot beachgoer can tell you. Even under normal conditions, it is difficult for plants to establish themselves in coastal dunes. These areas are also subject to powerful storms, such as hurricanes. Wind and water from these storms can remove entire dune systems.

As discussed earlier, differences in slope, aspect, and exposure can create different microclimates. These factors lead to fairly predictable zones in coastal dune communities (Figure 12). The zone closest to the sea (foredune) receives the most disturbance from wind, salt spray, and storm surges. The temperature fluctuates widely due to lack of shade and lack of water in the substrate. The foredunes can only be colonized by the few pioneering species adapted to the harsh conditions. The interdune area behind the foredune is protected from some of the wind and flooding. When it floods, salt water may remain longer on the flatter areas. As water evaporates, leaving the salt behind, the sand can become very salty. This leaves mostly salt-tolerant plants in this zone. The back dune is farthest from the highest winds and flooding, allowing more vegetation to establish itself and survive.

https://commons.wikimedia.org/wiki/File:Texel_-_Bleekersvallei_-_Panorama_View_on_North_Sea_dunes_%26_beach_03.jpg

Figure 12. Coastal sand dunes in Bleekersvallei Nature Preserve, De Koog, Netherlands.

**Analyze the Figure**

- What patterns do you see in vegetation going from the sea inland?
- What is the likely relationship between disturbance and distance from the sea?

A team trying to restore coastal dunes in Florida's St. George Island State Park discovered a potential case of facilitation. In 2008, the team planted several species of native plants to help stabilize dunes that had been damaged by storms. Once vegetation is established, it can help to hold dunes in place, add organic material, and provide shade. The restoration team wanted to measure the success of their efforts, so they established control plots where they did no plantings. When they later compared the experimental and control plots, they found an increase in the plants they had planted on the experimental sites, as they had hoped. They were surprised to also find an increase in native species that they had not planted on the experimental sites.

They investigated what had happened by doing another set of experiments to see whether plantings would change the dune community by increasing the total vegetation coverage or number of species (species richness). If so, they were interested in the mechanism of the effect. Did the plantings facilitate other species by increasing shade (which would preserve water and keep the site cooler)? Did the plantings facilitate other species by changing water dynamics under the soil? Desert plant roots have been shown to help keep water nearer the surface. This could benefit neighboring plants. Finally, they wondered whether the plantings themselves made a difference. It was possible that just disturbing the substrate brought seeds or other plant

parts to the surface where they could sprout. If disturbance alone were enough to stimulate native plant growth in dunes, restoration efforts would be much cheaper and faster.

To summarize, the researchers tested the following hypotheses:

1. Plants improve the dune environment for other plants
2. Shade improves the dune environment for plants
3. Plants improve soil moisture, improving the dune environment for other plants
4. Soil/sand disturbance improves the dune environment for plants

Note that hypotheses 2 and 3 provide possible mechanisms for hypothesis 1, in other words, they are possible explanations for how plants could facilitate the growth of other plants. Hypothesis 4 would explain why the restoration work increased plant growth, even if there were no facilitation of plant recovery by plants. Normal plant growth from seeds or ramets (bits of plants that produce clones) would not lead to soil disturbance. The hypotheses do not necessarily contradict each other. All could be correct. If hypotheses 2 and 3 were correct, this would probably mean that hypothesis 1 was correct, unless the benefits of shade and soil moisture from plants were balanced by inhibitory effects of plants.

The hypotheses would lead to specific predictions:

1. Plantings would increase total vegetation coverage or number of species, compared to controls.
2. Shading by objects other than plants would increase total vegetation coverage or number of species, compared to controls.
3. Plantings would increase soil moisture, compared to controls.
4. Disturbance of soil alone would increase total vegetation coverage or number of species, compared to controls.

The team set up plots in the three dune zones. These sites had been exposed by the previous year's storm. In the restoration treatment, researchers dug holes and placed native plants in them. In the disturbed treatment, the same type of holes were dug, but no plants were placed in the holes. In the shaded treatments, shade cloth was staked out to mimic the amount of shade that plants would normally provide. Six months later, researchers measured the species richness and plant cover on the sites (Figure 13).

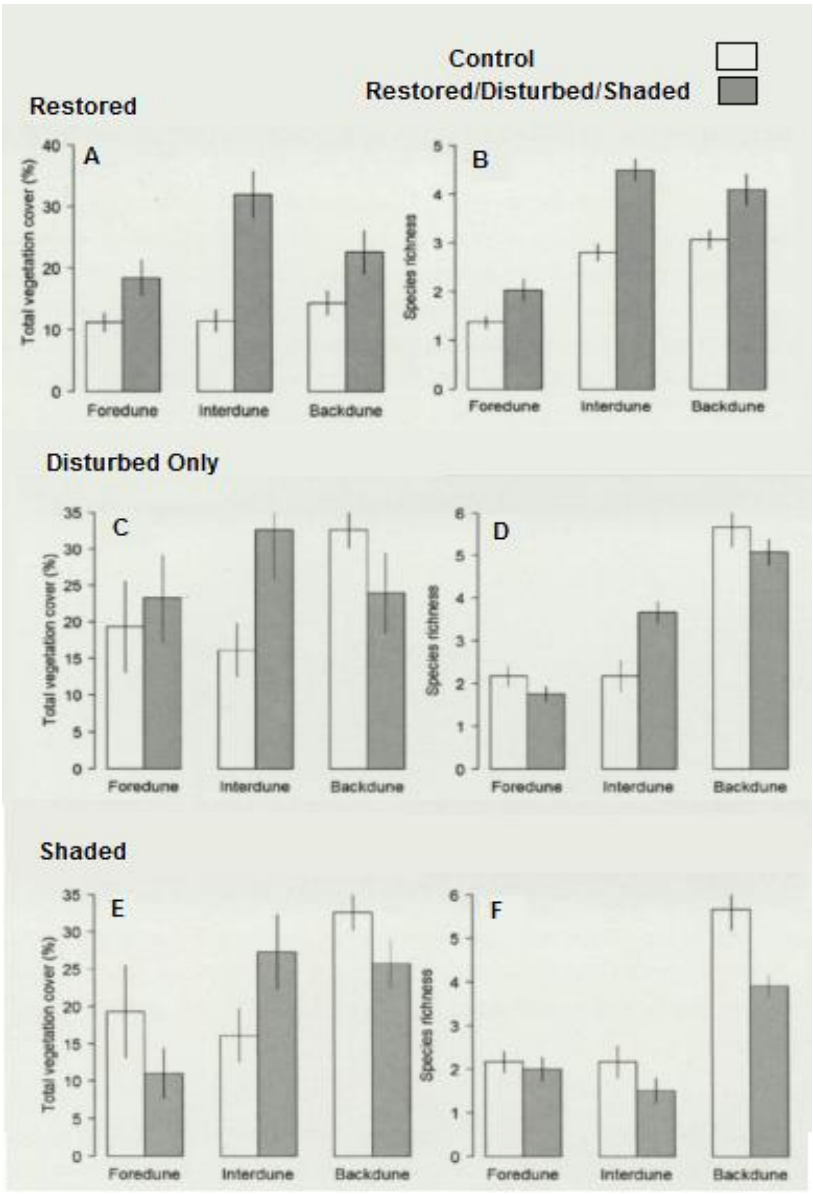



Figure 13. Mean (+/- SE) vegetation cover (A, C, E) and species richness (B, D, F) on dunes following treatments. Restored plots (A & B) were planted with native species. Disturbed Only plots (C & D) received no plantings. Shaded plots (E & F) had shade cloth canopies. Modified from: Monge, J. A., & Gornish, E. S.. (2015). Positive Species Interactions as Drivers of Vegetation Change on a Barrier Island. *Journal of Coastal Research*, *31*(1), 17–24.

**Analyze the Figure**

- Did planting with native species increase vegetation cover or species richness compared to controls?
- Did disturbing the substrate increase vegetation cover or species richness compared to controls?
- Did shade increase vegetation cover or species richness compared to controls?

Researchers didn't expect disturbance to cause significant differences in the foredune area because disturbance is already a common occurrence in this zone. Diversity is also always low in the foredune for the same reason, so researchers didn't expect any large increases in foredune diversity in any of the treatments.

A separate set of measurements tracked below-ground water movement using electronic sensors. The restoration plots had higher soil moisture than controls in the foredune and interdune zones, but the control plots were wetter than the restoration plots in the backdune zone.

Which hypotheses are supported by the data?

1. Plants improve the dune environment for other plants
2. Shade improves the dune environment for plants
3. Plants improve soil moisture, improving the dune environment for other plants
4. Soil/sand disturbance improves the dune environment for plants

Which of these are evidence of facilitation, plants improving the habitat for other plants? If you were making management recommendations about restoring storm-damaged dunes, would you recommend doing plantings of native species, erecting shad cloth over areas of the dunes, or digging holes around the dunes to encourage sprouting of new plants? Explain your reasoning.

**Case Study Part 3: What's Ahead for Pripyat?**

The communities in the exclusion zone continue to change. Two major factors that determine the community are reproduction and persistence (how long the individual trees live). Because trees can live a long time, even species that are not currently reproducing have not necessarily disappeared. Researchers at Pripyat divided the tree species into four different regeneration patterns (Table 3). All trees need sunlight for photosynthesis. Some species are more sensitive to shade than others, especially in the seedling stage. Even trees that have a high shade tolerance will have reduced growth and survival when shading is extreme.

Table 3. Reproduction patterns of trees in the Pripyat exclusion zone. Some did not regenerate at all and are not listed on the table. Based on: Laćan, I., McBride, J. R., & De Witt, D. (2015). Urban forest condition and succession in the abandoned city of Pripyat, near Chernobyl, Ukraine. *Urban Forestry & Urban Greening*, *14*(4), 1068-1078.

| Pattern | Characteristics |
|---|---|
| 1 | Fast regeneration, reproducing into 2015. Medium or high shade tolerance. Seedling survival and growth expected to decrease as shading increases. |
| 2 | Fast regeneration, but no reproduction by 2015. Shade-sensitive. Little reproduction expected in future due to shading. |
| 3 | Delayed regeneration but reproducing into 2015. Medium or high shade tolerance. Seedling survival and growth expected to decrease as shading increases. |
| 4 | Delayed regeneration, reproduced before 2015, but stopped. Shade-sensitive. Little reproduction expected in future due to shading. |

Using information on the reproduction patterns and the lifespans of the trees, the researchers made projections about what the tree community would be like in 200-300 years. Some short-lived trees that are not shade-tolerant have already disappeared from the community, others are expected to do so in about the next 25 years as the seedlings that survived in the open areas die of old age. For example, willows show pattern #2. They reproduced right after the disaster, then stopped. Willows do poorly in shade and most have died.

Trees with intermediate shade tolerance and life spans will disappear next. After about 200 years, the Pripyat forest is expected to contain mostly long-lived trees that can tolerate the shade of dense forest, such as oak and maple. This will be the climax community.

Poplars and aspens may still survive for centuries at forest edges and on pavement, where other species cannot grow well. Eventually, however, the pioneering trees will break up the concrete and asphalt enough to allow their competitors to invade, producing shade that will doom the poplars and aspens. This is an example of facillitation While species composition is changing, the former city is now home to tall groves of trees (Figure 14).

https://commons.wikimedia.org/wiki/File:Chernobyl_Exclusion_Zone_%282015%29_77.JPG

Figure 14. Area in the Chernobyl Exclusion Zone in 2015. For photographs of the same sites before the 1986 evacuation and in 2011-2012, see https://www.depts.ttu.edu/nsrl/get-involved/downloads/chernobyl-exhibit.pdf.

As with any community, the successional stages could be interrupted by disturbances. Fires are an obvious possibility for forests. If trees burned, the radioactive isotopes in the wood would be released into the air, contaminating areas far away from the exclusion zone. To avoid this, any forest fires in Pripyat would probably be fought vigorously, but not all firefighting efforts are effective. As buildings collapse and their sites are invaded by plants, a mosaic of different stages might develop.

**Learning from the Case Study**

- Identify an example of one species facilitating the growth of another.
- How does tolerance influence community composition in Pripyat?
- Describe how random events might make the future of Pripyat difficult to predict with certainty.

**Check Your Understanding**

- How do the tolerance and inhibition models differ?
- Why might facilitation be more common in early successional stages?
- How do life history traits of individual species influence successional changes? Give an example.

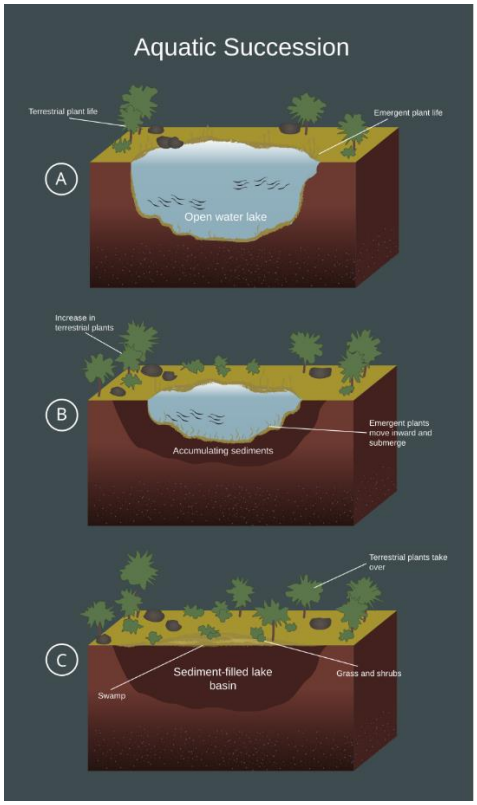
### Aquatic Systems Have Successional Stages

When new habitat opens in aquatic systems, such as when a new lake forms, when a new rock falls into the water, or a dead whale falls to the bottom of the sea, colonizers will move into the habitat. Later, they may be replaced by species that are better competitors. The habitat may

also be changed in ways that make it better or worse for species that come later. Unlike terrestrial systems, plants may have a smaller role in the successional stages.

Lakes have a specific type of succession. Lakes can be formed by major disturbances, such as glaciers or floods scooping out earth, volcanos that fill with water when they are inactive, or earth movements causing areas to sink and rise. They can also be formed by smaller events, such as a rockslide that holds water behind it. Beavers are famous for creating dams that hold back water. Human-made dams form artificial lakes called reservoirs.

As rivers and streams enter the lakes, they carry soil and other material. Faster water currents carry larger material. When the speed of the water drops, the material in the water falls out of suspension. Over time, this sediment fills in the lakes (Figure 15). As vegetation takes root, the plants trap more sediment. When lakes are so shallow that plants rooted in the bottom can reach above the water, they become marshes. Eventually, they may fill in completely and become meadows, forests, or other ecosystems. This will happen more quickly in shallow lakes, or where more material is carried in by rivers and streams. The more erosion there is upstream, the more sediment there will be downstream. The material that fills in the lakes can also be washed out by flooding. This will bring the lakes back to an earlier successional stage.




By Dhrithi Vishwa - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=148792493

Figure 15. Successional stages in a lake. Sediments from rivers and streams can gradually fill lakes until they disappear. Flooding can wash out the sediment and return the lake to an earlier stage.

**Analyze the Figure**

- Why did the lake become shallower?
- What was the final successional stage?

Aquatic systems are heavily influenced by water flows. Currents and floods can wash organisms downstream, even scrape organisms off surfaces. In areas where precipitation or snow melt send large volumes of water downstream, these events will be larger and more powerful. Recolonization may begin again when flows are slower.

On the other extreme, dry seasons or droughts can turn wetlands, rivers, or streams into dry beds. When the water flows again, organisms may be carried in with the water to repopulate the area (Figure 16). Other organisms may already be in the sediment in a form that can survive drying out. For more discussion of how flooding can be both important and controversial, see **Why it Matters: Flooding Grand Canyon.**

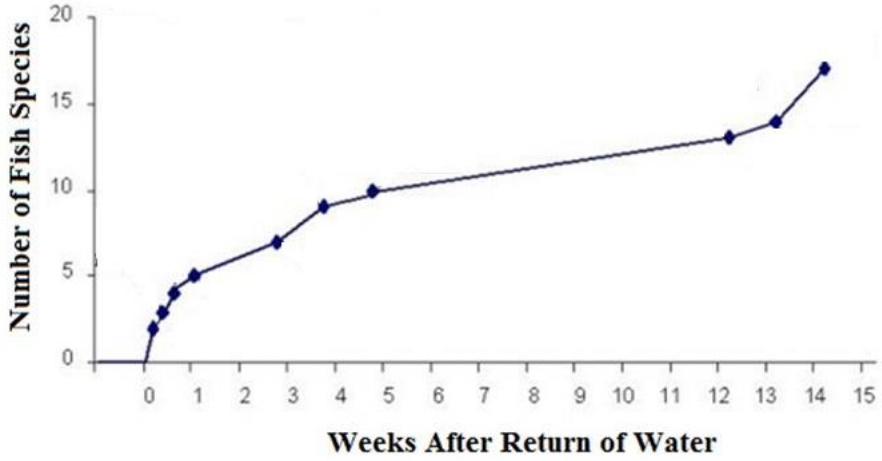



Figure 16. Recolonization of a Florida wetland by fish after re-flooding. Modified from: Loftus W.F., Bruno, M.C., Cunningham, K.J., Perry, S., and Trexler, J.C.. 2013. The Ecological Role of the Karst Wetlands of Southern Florida in Relation to System Restoration. http://water.usgs.gov/ogw/karst/kigconference/wfl_ecologicalwetlands.htm

**Analyze the Figure**

- When are changes in the fish community most rapid?
- How long does it take for about half the total number of fish species to colonize the wetland?

**Why It Matters: Flooding Grand Canyon**

Burton, 2011

Figure 17. Beach on the Colorado River of Grand Canyon.

The Colorado River is named for the red color of its sediment. It carved Grand Canyon over millions of years. Until about half a century ago, river flows depended on natural events, such as snow melt and storms. Natural floods moved sediment and swept plant communities off beaches. Species in the canyon were adapted to huge variation in river flows.

The Glen Canyon Dam was built just upriver from Grand Canyon in 1963 to generate electric power and store water for human communities. The power company releases water according to power demand, so there are daily changes in water level. Power companies lose the opportunity to make millions of dollars when they release water that is not generating electric power.

Before the dam, sediment from upstream built and maintained sandy beaches along the Colorado River. When water is trapped in the reservoir behind the dam (Lake Powell), most of the sediment settles out. The Glen Canyon Dam gets 100 million tons of sediment every year, on average. Without the input of silt from upstream, the beaches in Grand Canyon are eroding away. Daily changes in water level speed up the erosion, leaving less natural habitat. The dam also stopped all floods in Grand Canyon for decades. Some native species suffered, and invasive species moved in. Conservationists want periodic flooding to restore some of the natural disturbance to the Grand Canyon Ecosystem.

**Continued**

**Why it Matters: Flooding Grand Canyon, cont.**

Each year, over 20,000 people run the Colorado River through Grand Canyon. There are few places to enter and leave the canyon, so boaters must camp on the shrinking beaches. Without flood waters to disturb them, shrubby plant communities are covering more of the beaches that are left. Professional and recreational river runners want to see more major releases of silt-filled water to clear vegetation and build up new beaches.

Experimental planned “floods” helped to build up some beaches, but much of this new beach area eroded away. Regular flooding may be used in the future.

- Who would be affected most by increasing the cost of electricity?
- Some people argue that rivers belong to the people and companies should not have a say in how the river is managed. Do you agree?
- If the power demand must be met by burning fossil fuels, does this pose a greater environmental threat than a lack of flooding?
- Only a small percent of the US population will ever raft through Grand Canyon. Should this give them less say about river management?
- If you were part of a group managing the water flows, what questions would you ask?

**Check Your Understanding**

- Describe some ways that aquatic and terrestrial succession are different.
- Describe some ways that aquatic and terrestrial disturbances are different.
- Will biomes and substrates influence aquatic successional changes? Explain your reasoning.

**Stability Takes Multiple Forms**

The ecological **stability** of a community refers to the community's ability to withstand disturbance without being destroyed. Some communities are fragile. Even small disturbances cause the community to change to an entirely different set of species. Other communities persist despite disturbances. For example, imagine that a microbial community inhabits puddles of water. Increasing temperature could be a major disturbance. When the water temperature rises, are some species lost, while others invade the community? If so, the community has a low stability. The stability of a community is a function of the properties of individual species and their interactions.

Stability can be the result of different processes (Figure 18). A community is **resistant** to disturbance if the disturbance does not cause a change in the species that make up the community. For example, when a grassland burns, the same species re-sprout.

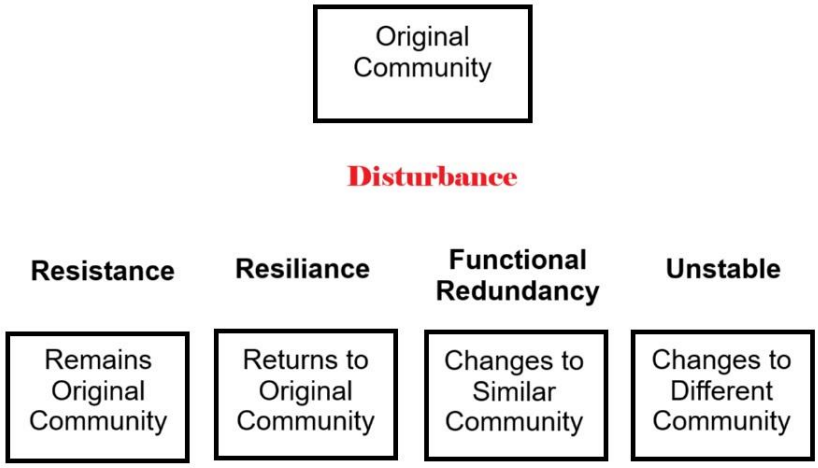


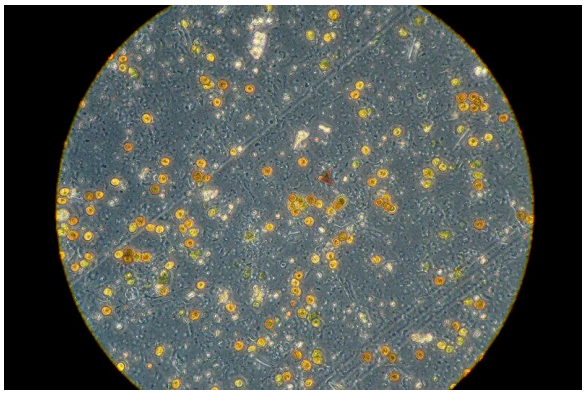

Figure 18. Stability can take the form of resistance, resilience or a return to a community composed of species that function similarly to the original community.
Based on: Allison, S. D., & Martiny, J. B. (2008). Resistance, resilience, and redundancy in microbial communities. *Proceedings of the National Academy of Sciences*,*105*(Supplement 1), 11512-11519.

**Analyze the Figure**

- Which types of stability lead to maintaining the same species in a community?
- Which types of stability lead to successional changes in a community?

A community that is **resilient** returns to its earlier state after a disturbance. The same species recover or recolonize the area. Communities of intertidal invertebrates are exposed to disturbance from debris that crash into them, removing individuals (Figure 19). New individuals of the same species can move into unoccupied space, making the intertidal communities resilient to the disturbance caused by storms.

A community might also be wiped out by a disturbance but return to its normal function if the original species were replaced by species that had similar niches. Such a community would be **functionally equivalent** to the original community. For example, coral depend on symbiotic algae called zooxanthellae that do photosynthesis (Figure 19). Some species of zooxanthellae are being killed by rising sea temperatures. If different species of zooxanthellae were able to re-colonize the coral, the community would still function as a coral reef, despite some changes in the species in the community. The new community would be functionally equivalent to the former community.



https://commons.wikimedia.org/wiki/File:Zooxanthellae_Stylophora_pistillata.jpg

Figure 19. Zooxanthellae isolated from coral. These algae provide carbohydrates made using photosynthesis and receive nitrogen from coral, which are animals.

The severity of the disturbance, how often it occurs, and the type of disturbance will also be important in determining whether a community will continue after the disturbance. Even a community that is adapted to a particular type of disturbance may be replaced if the disturbance is too frequent, too large, too, prolonged, or too damaging. For example, many plants are adapted to grazing. However, if the community is overgrazed, it can still be damaged so much that it will change into an entirely different community, even one that contains few plants. Desertification is the transition of one type of community, such as grassland or forest, into a desert-like community with much lower productivity. Erosion, changes in water relations, temperature and other factors may prevent a transition back to the previous community. Many communities use sand fences to try to stabilize sand and prevent further erosion (Figure 20).

https://commons.wikimedia.org/wiki/File:Anti_desertification_sand_fences_south_of_the_town_of_Erfoud,_Morocco.jpg

Figure 20. Anti-desertification fences, like these in Erfoud, Morocco are used to try to stabilize sand.

**Check Your Understanding**

- Which types of stability lead to maintaining the same species in a community?
- Which types of stability lead to successional changes in a community?

**Some Species Specialize in Surviving Disturbance**

Disturbance is essential for some communities because individual species are adapted to specific disturbances. For example, long-leaf pines grow in sandy, nutrient-poor soil in the coastal southeastern US. When a long-leaf pine sprouts, it invests very little in above-ground growth. It puts most of its resources into the roots. For several years it may have only a cluster of needles showing above the ground (Figure 21). If a fire burns through the forest, the seedling loses almost nothing. Its saved resources are protected underground.

http://dcm2.enr.state.nc.us/wetlands/coastal_explorers/cpfmodule/bays/bays_rims2.htm

Figure 21. Longleaf pine (*Pinus palustris*) in its "grass stage." It may remain in this stage for 5-12 years, gathering resources in its roots.

Many potential competitors may be killed by fire. The long-leaf pine is now free to grow very quickly. There will be little fuel available to burn for a few years, so it is fairly safe from fire. A thick bark forms to protect it from fire's heat. As it grows taller, it drops its lower branches off. When the next fire burns through, the flammable needles will be high up in the sunlight, away from ground fires, making the pine resistant to the fire. Any ground fires now will help the pine by clearing competitors away from its offspring and returning nutrients to the soil.

Long-leaf pines inhibit their competitors. They drop flammable needles that make excellent fuel and encourage forest fires. When long-leaf pines colonize an area, they reduce the ability of non-fire adapted species—such as oaks—to colonize the area. For a discussion of the evolution of adaptation to fire in another system, see **Evolutionary Perspective: Pines, fire, and squirrels**.

**Evolutionary Perspective: Pines, fire, and squirrels**

Lodgepole pine trees in the dry regions of the western United States have evolved several traits that make them resistant to disturbance from small ground fires. Their bark is tough, and they drop their lower branches, so fire can not reach the needle-filled upper branches. Large "crown" fires occasionally burn the upper branches and can kill all the trees in a large area. This is the perfect time for a lodgepole pine to have its seeds sprout because there is no competition for light or water. The parent trees are no longer around, but their seeds can be. Pine trees produce their seeds inside of cones. In many species, these cones open when the seeds are mature. In some species, pines can produce cones that will only open when exposed to fire. This way, seeds are not wasted when there is too much competition, and the cones from many years will be ready to drop their seeds after a fire. This makes lodgepole communities resilient, meaning that they recover after fires.

The type of cones that lodgepole pines produce is determined by genetics. Some areas have many trees that produce fire-opening cones, other areas have few. Why hasn't natural selection removed the trees that don't produce fire-opening cones? Because fire is not the only factor that influences the fitness of the pines (Figure 22).

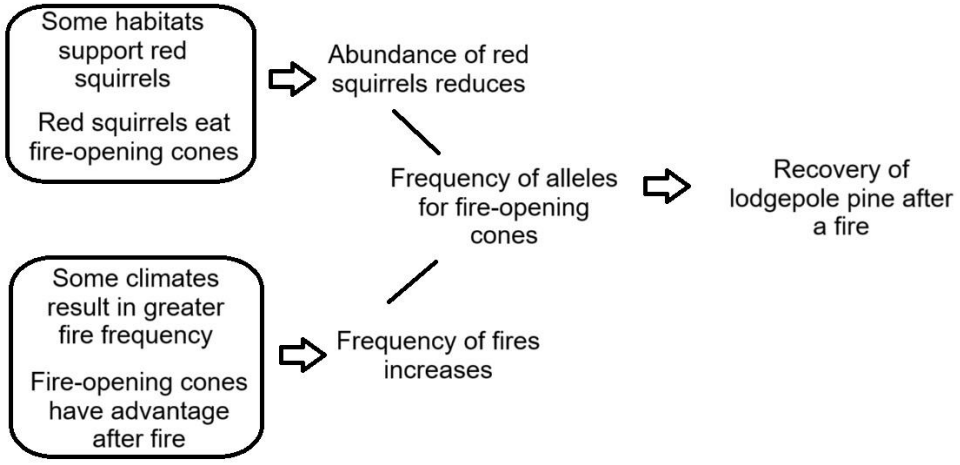



Figure 22. A visual model of the influence of genetics, climate, and red squirrels (*Tamiasciurus hudsonicus*) on lodgepole pine (*Pinus contorta*) recovery. Based on: Talluto, M. V., & Benkman, C. W. (2014). Conflicting selection from fire and seed predation drives fine-scaled phenotypic variation in a widespread North American conifer. *Proceedings of the National Academy of Sciences*, *111*:9543-9548.

**Continued**

**Evolutionary Perspective: Pines, fire, and squirrels, cont.**

**Analyze the Figure**

- Which types of disturbance lead to more fire-opening cones in a lodgepole community?
- How does cone type influence tree density in a lodgepole community?

Most animals avoid the tough, sticky, fire-opening cones, but red squirrels collect cones and store them in large piles. The red squirrels spend much of their active time harvesting cones, defending their cone piles from other red squirrels, and eating pine seeds.

Where fires are more common, the advantage of fire-opening cones is higher than the cost of having squirrels eat the seeds. Where fires are less common, the advantage of cones that open without fire is higher because they are less likely to be eaten by the red squirrels.

Areas without fire-opening cones do not recover from fires as quickly. The density of young trees is lower and the trees tend to grow in small patches. Growth of new trees has dramatic influences on erosion, succession, nutrient cycles and other ecosystem processes. The actions of small squirrels influence patterns across entire landscapes in lodgepole pine habitat.

**Make a prediction:** Fires were common in dry western forests before European settlement. In the early 1900s, the U.S. Government began aggressively fighting fires to preserve valuable forests. Today, fire is used as a management tool. Some fires are put out as soon as possible. Others are allowed to burn unless they threaten people and property. How will changing fire management influence the frequency of genes for fire-opening cones? How might changes in fire management influence red squirrels?

**Model Skill: Scatterplots**

Scatterplots are used to explore the effect that one variable has on another. If one variable tends to increase when the other variable does, this is a **positive correlation**. If one variable goes up when the other variable goes down, this is a **negative correlation**. As discussed in Chapter 1, correlation does not prove that the independent variable caused the change in the dependent variable, but it is evidence.

A team of researchers burned leaves of multiple species under controlled conditions to see how they might influence the start and spread of fires in the wild. They used leaves with different levels of terpenes (which are flammable chemicals made by long-leaf pines and other trees) and measured the speed of fire spread (Table 4).

Table 4. Effect of leaf terpenes (log of concentration) on rate of fire spreading.
Based on Ormeno, E., Cespedes, B., Sanchez, I. A., Velasco-García, A., Moreno, J. M., Fernandez, C., & Baldy, V. (2009). The relationship between terpenes and flammability of leaf litter. *Forest Ecology and Management*, *257*: 471-482.

| Log Leaf Terpene Concentration (µg/gDM) | Fire Spread Rate (m/s) |
|---|---|
| 2.4 | 5 |
| 2.45 | 9 |
| 2.5 | 6 |
| 2.5 | 8 |
| 2.6 | 6 |
| 2.6 | 12 |
| 2.8 | 16 |
| 3.3 | 17 |
| 3.5 | 16 |
| 3.5 | 18 |
| 3.9 | 20 |

Make a scatterplot from the data in Table 4. Start by determining whether terpene content in the leaves is the dependent variable or the independent variable (see Chapter 1). If you expect terpenes to influence the spread of fire, terpene level would be your independent variable. If you expect fire spread to determine the terpene level in the leaves, fire spread would be your independent variable. Label the X-axis with the independent variable. Include the units. Label the Y-axis with the dependent variable and units.

**Continued**

**Model Skill: Scatterplots, cont.**

Plot the data in Figure 23. For example, with a terpene concentration of 2.4 µg/gDM, the fire spread 5 m/s. Find 2.4 on the X-axis, then go up to 5 on the Y-axis, and make a dot. Plot the remaining points.

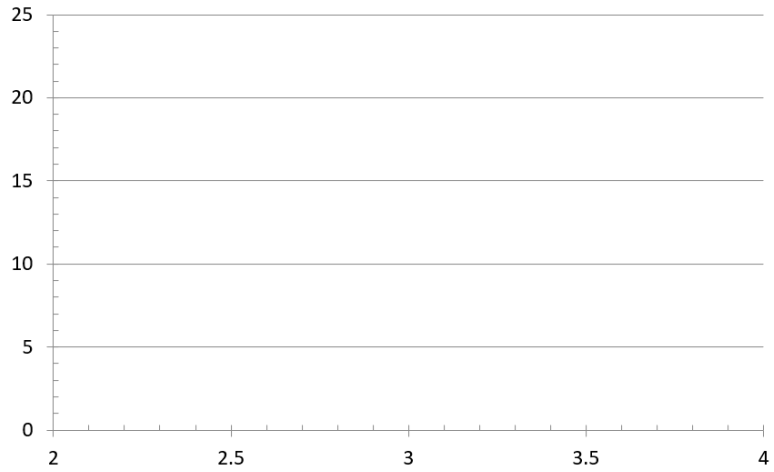



Figure 23. Relationship between terpene content and fire spread. Plot the data in Table 4 to show the relationship between the two variables. Label the axes with the name and units of the variable.

**Analyze the Figure**

- Use the axis labels to help you write a sentence that tells the story of the data. Use this as your graph title.
- If the log leaf terpene concentration were 3 µg/gDM, what would the fire spread rate be? Predicting a value between known values is **interpolation**.
- If the log leaf terpene concentration were 4.5 µg/gDM, what would the fire spread rate be? Predicting a value beyond the range of known values is **extrapolation**. It may be very inaccurate because the trend of the model may be very different outside of the range of the data you have. For example, it may level out.

**Check Your Understanding**

- How can disturbance help some species?
- If a species is adapted to one type of disturbance, is it likely to be resistant to other types of disturbance. Explain your reasoning, using an example.

# Key Concepts

- Disturbances change the composition of a community, and trigger a fairly predictable series of changes, called succession.
- Early successional stages are dominated by pioneer species that colonize rapidly, succeed in open areas, and invest heavily in reproduction.
- Later successional stages are dominated by species that compete effectively in a crowded environment.
- Disturbances influence community diversity, productivity, and biomass.
- Successional stages are specific to habitat type (terrestrial or aquatic), local conditions, the type of disturbance, and the nature of the disturbance.
- Community interactions may benefit or harm species, influencing successional changes.
- Communities differ in their ability to survive or rebound from disturbances.
- Some species are adapted to specific disturbances.

# Apply the Concepts

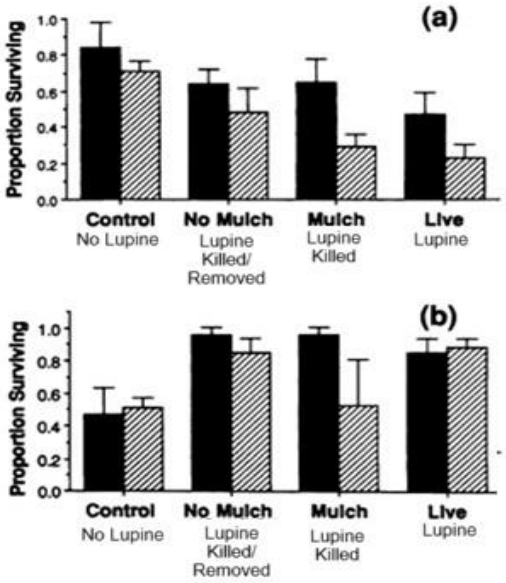
**Learning Outcomes**

1. *Accurately describe and explain the effects of different disturbances on communities.*
2. *Make and defend reasonable predictions about community changes following disturbances.*
3. *Accurately relate characteristics of species to successional changes in communities.*
4. *Relate successional stages to climate and other environmental conditions.*

1. If a volcanic island rises from the ocean, is this an example of primary succession or secondary succession? How will this be different from succession that happens after a fire? *(Learning Outcomes 1 and 2)*

2. Mount St. Helens erupted in 1980. A huge area was covered deep in ash and volcanic rock. Lupine is a native plant that lives several years. It is a legume, so it has bacteria near the roots that add nitrogen to the soil. Researchers tested the effect of lupine on two invasive perennial plants: pearly everlasting and fireweed (Figure 24). They grew these invasive plants in a greenhouse, then moved them into plots of four different types. Control plots had no lupine. No Mulch plots had lupine killed and all dead vegetation

removed. Mulch plots had lupine killed but left in place. Live plots had living lupine.




First year survival

Second year survival—Proportion of first-year survivors that survived second year.

Figure 24. Mean (+ standard error) of seedlings surviving. Black bars = pearly everlasting. Striped bars = fireweed. Adapted from Morris, W.F. and Wood, D.M. (1989). The role of lupine in succession on Mount St. Helens: Facilitation or inhibition? *Ecology*, 70: 697-703.

A. Which plot had the highest fireweed survivorship in the first year?
B. Explain whether this is an example of facilitation, inhibition, or stress tolerance. What evidence supports your position?
C. Which plot had the lowest pearly everlasting survivorship in the second year?
D. Explain whether this is an example of facilitation, inhibition, or stress tolerance. What evidence supports your position?
E. Predict whether fireweed will become more common on this site. What evidence would strengthen your argument?

*(Learning Outcomes 1, 2, and 3)*

3. Refer to Figure 25.

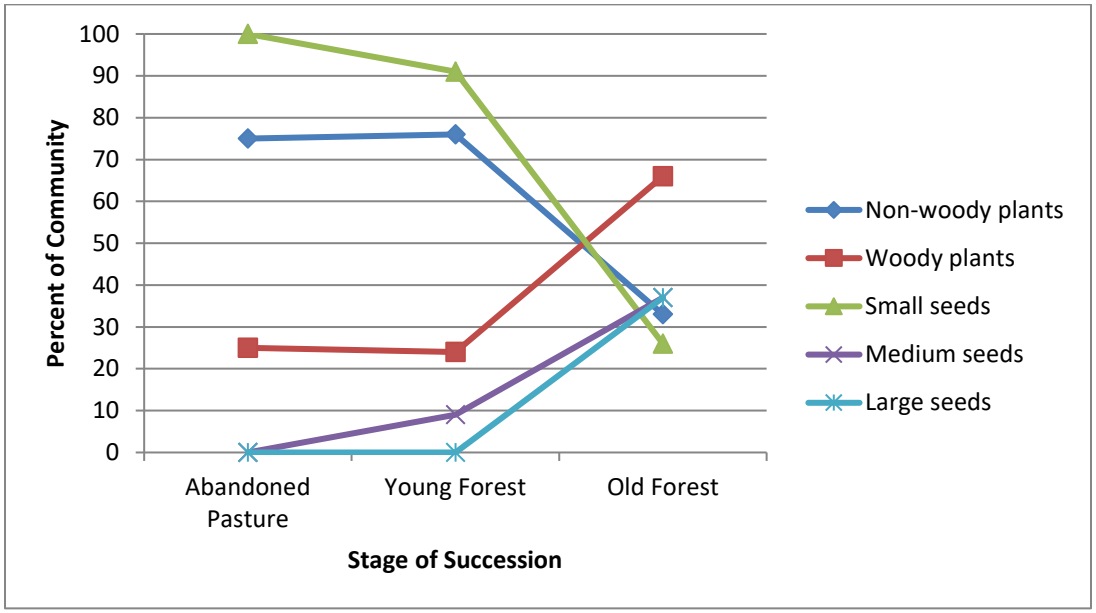



Figure 25. Percent plants and germinating seeds in a forest preserve in Brazil. The groups are not individual species; they are types of plants. Drawn from data in: Leitão, F.H.M., Marques, M.C.M. & Ceccon, E. (2010). Young restored forests increase seedling recruitment in abandoned pastures in the Southern Atlantic rainforest. *Revista de Biologia Tropical*, 58: 1271-1282.

A. Describe the most important difference between the forest stages.
B. Explain these changes. What characteristics of the plants make them perform better at different stages?
C. Predict which stage will have the highest productivity and explain your answer. *(Learning Outcomes 1, 2, and 3)*

4. Imagine that a severe flood removes all the vegetation from a temperate forest. Then imagine the same flood in a desert. Which community will recover faster? Why? *(Learning Outcomes 2, 3, and 4)*

**Unit V: Communities**

# Chapter 17: Biodiversity

### Case Study Part 1. Slash and Burn in Biodiversity Hot Spots

https://en.wikipedia.org/wiki/Slash-and-burn#/media/
File:Bolivia_slash_%26_burn_lo_(4386225275).jpg

Figure 1. Agricultural field carved out of a tropical rainforest using the slash-and-burn method. Mature rainforest is in the background.

**Biodiversity** refers to the variety of species (or other taxonomic groups) in an area. Tropical rainforests support many species per unit area, making them biodiversity **hot spots**. A large percentage of Earth's species lives in the tropical rainforest biome. These species keep carbon out of the atmosphere, provide food and building materials, and may hold the key to life-saving medicines. They are also threatened by slash-and-burn agriculture. This practice involves cutting and burning forests to provide agricultural land. The cleared areas may be used by local people to feed their families or by large corporations shipping beef, soybeans, and other products to other nations, including the United States.

This chapter will explore how biodiversity is measured, what influences biodiversity, how biodiversity influences ecosystems, and what can be done to conserve biodiversity.

**Learning from the Case Study**

- What is biodiversity?
- Why might biodiversity in tropical rainforests be high?
- What are some of the threats to tropical rainforests?

# Learning Outcomes

1. *Accurately analyze patterns of diversity*
2. *Draw reasonable conclusions about extinction risks*
3. *Evaluate consequences of changes in biodiversity*

**Vocabulary Toolkit**

**Roots**

Hetero = different
Homo = same

**Opposites**

Native species and Introduced species
Heterogeneous and Homogeneous

**Word Watch List**

**Biodiversity**: Variety of organisms, can be measured in various ways
**Hot spot**: Area with high biodiversity
**Richness**: Number of species in an area
**Native species**: Species that evolved in a given area
**Introduced species**: Species that evolved in a different area than where they are
**Abundance**: Number of individuals of a species
**Proportional abundance**: Abundance divided by number of individuals in all species
**Evenness**: How equal the proportions of different species are
**Endemic species**: Species that occur in the wild only in a specific area
**Heterogeneous:** Containing patches with different characteristics
**Homogeneous:** Entire area is fairly similar
**Invasive species**: Species that spread rapidly, usually displacing native species
**Meta-analysis**: Research based on other studies or data sets
**Rarefaction**: Adjusting diversity measurements to compensate for abundance or sampling effort

**Biodiversity is Usually Estimated**

How many species are there on Earth? No one really knows. Over 1 million have been named, but it is impossible to know how many have not. It helps if the species are large enough to see without special equipment or effort. It helps if they live in places that are accessible and well-known. It helps if they are common. Many species do not fit these categories, but we don't know how many. Researchers are still finding mammal species, so it would not be surprising if there are many more microbes in the world. Estimates for the total number of species on Earth tend to be somewhere between 5 million and 100 million. Some species will be lost before they are ever identified. Each species lost means a loss of the information in their genomes. To understand the significance of lost species to human health, see: **Make the Medical Connection: Medicinal Plants**

**Make the Medical Connection: Medicinal Plants**

https://en.wikipedia.org/wiki/Catharanthus#/media/File:Catharanthus_roseus_6576.JPG

Figure 2. Madagascar periwinkle (*Catharanthus roseus)* is one of many tropical plants that has been the source of life saving medicines.

Before 1970, children with leukemia had only about a 10-20% chance of survival. Thanks to the medicinal properties of a plant discovered in a Madagascar rainforest, survival rates today are about 80-95%. The chemical found in this plant is now synthesized. This is a good thing, because deforestation has now made this plant extinct in the wild. Many prescription drugs were originally derived from plants, especially rainforest species. Species are lost every day. There is no way to know whether any of them could have helped to defeat deadly diseases.

The number of species in a location is called species **richness**. While a community consists of all species in an area, ecologists are often interested in some subset of the total biodiversity. For example, researchers may be interested in biodiversity of microbes in the soil or the biodiversity of marine invertebrates on coral reefs. They may use the estimate of richness for

one taxonomic group to make inferences about the overall biodiversity of an area. The presence of **native species** (those that evolved in the area) often signals a higher habitat quality than the presence of **introduced species** (those that were moved into the area by human activity).

Researchers must usually assume that the species richness they find is a reasonable estimate of the true species richness. Imagine that you wanted to know which bird species were using a local park at this time of year. You could walk through the park at different times of day, identifying and recording the birds you saw. The more time you spent, the more bird species you would be likely to spot, but at some point would you have seen every bird that uses the park in this season? Would you know whether there were still some you missed?

A species-area or species-effort curve (Figure 3) helps to estimate the true species richness. It shows the *cumulative* number of species found. Imagine that on your first day you saw five different bird species. On the second day you saw six species, but only two of them were species that you had not seen on day one. That would mean your cumulative number of species found by day two was seven (the five you saw on day one plus the two new ones). Eventually, you would be seeing only birds you had seen before and the line would flatten out (11 species in the example). There would always be the chance that you would see something new, but you would be fairly confident that you had identified most of the birds that use the park at this time of year. Carry out your own survey with **Do Try this at Home: Making a Species-Effort Curve**.

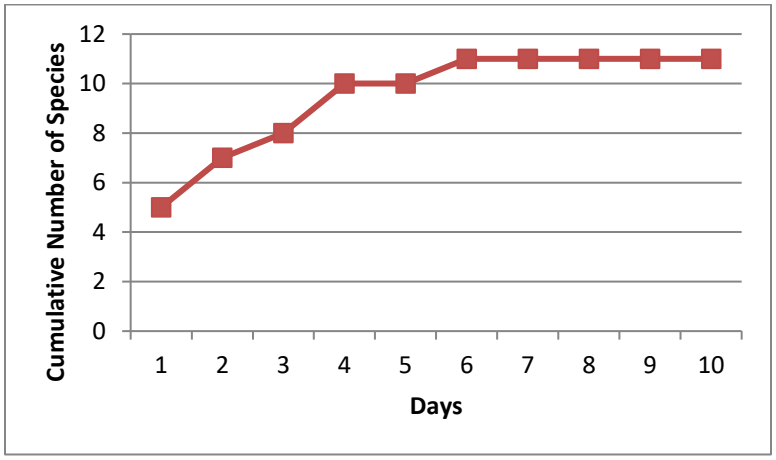



Figure 3. Hypothetical species-area curve. The line can be flat, but it can never go down because it is cumulative.

**Analyze the Figure**

- How many cumulative species had you seen by day 4?
- How many new species did you see on day 4?
- Do you think there are more than 11 species that use the study area? Explain your reasoning.

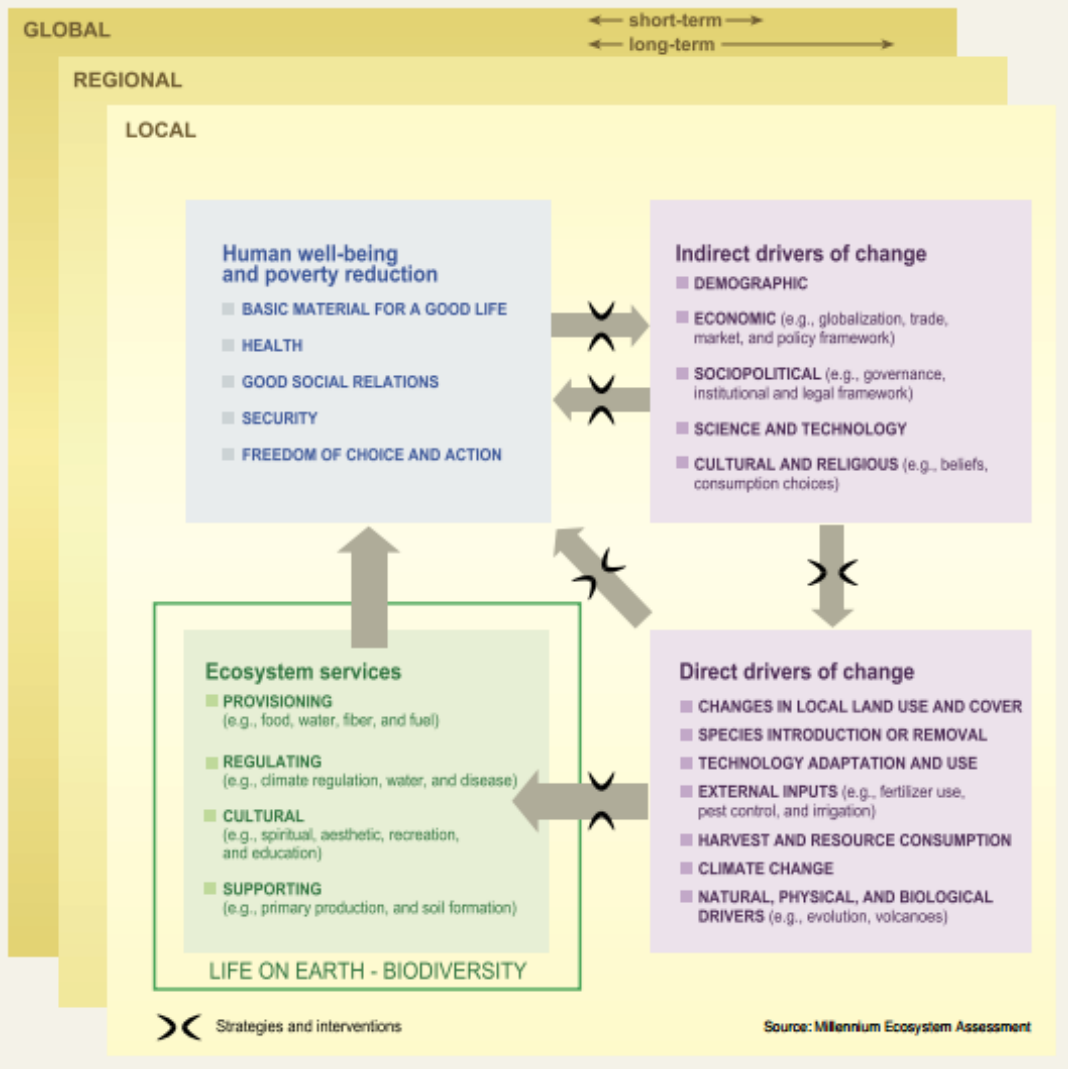
Similar patterns are seen when people sample larger and larger areas of plants, take more and more plankton samples, or increase the sampling effort in other ways. As the cumulative number of species increases, eventually the number of new species decreases. Researchers never know when they have found all of the species, but if a great deal of effort has produced no additional species, researchers can be reasonably confident that they have identified most of the species in that area. One exception is if the methods used are not appropriate for finding the "missing" species. For a discussion of why biodiversity is important to humans, see **Why It Matters: Ecosystem Services**.

**Do Try this at Home: Making a Species-Effort Curve**

Investigate diversity in your area to make a curve like the one in Figure 3. Find an interesting area and choose a group of organisms (e.g. birds, invertebrates, plants). Then systematically record the number of species you find in each block of time or space. For example, you might watch a bird feeder for one hour each day, turn over one rock at a time, or put a sampling frame down on a patch of plants. You do not need to know the actual names of the species you find, but you do have to be consistent in how you identify them (e.g. "red bird with pointy head," "centipede #3"). Taking pictures will help.

Record the species for each block, then graph the cumulative number of species for each block. You might make separate graphs for two areas that differ in some interesting way, such as an urban area compared to a park or the edge of a habitat to the center.

**Why It Matters: Ecosystem Services**




https://commons.wikimedia.org/wiki/File:MEAConservationStrategies.jpg

Figure 4. How a functioning ecosystem benefits humans and how humans threaten ecosystems.

Ecosystems provide all the necessities of life and many of the luxuries. Healthy ecosystems may depend on maintaining biodiversity. The loss of any particular species may not stop the ecosystem from functioning, but the loss of too many species, or even one key species, may disrupt the system so much that it will not recover.

- How do we put a monetary value on services such as pollination, seed dispersal, pest control, flood control, soil fertility, and other essential resources and services?
- Are humans obligated to protect future generations?

**Case Study Part 2. How Does Slash-and-Burn Influence Diversity?**

Slash-and-burn agriculture is not sustainable. Recall from Chapter 7 that rainforest soils are heavily leached of nutrients. Burning vegetation returns some nutrients to the soil, but crops quickly use these up, and farming becomes less and less rewarding. The areas are abandoned and farmers move on to new places. The tropical rainforest in the Rio Negro area of Venezuela has former farms that have been abandoned at different times. These sites reveal how biodiversity changes on abandoned farms (Figure 5).

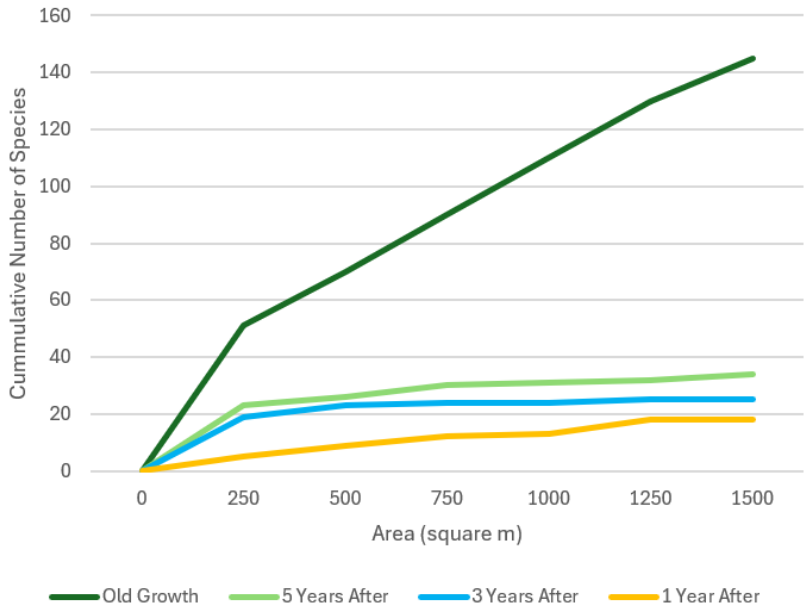



Figure 5. Species-area curves for trees at least 2 m tall in sites that had been used for slash-and-burn agriculture compared with old-growth forest in the same region. "Year After" refers to the time since the farms were abandoned. Based on: Uhl, C. (1987). Factors Controlling Succession Following Slash-and-Burn Agriculture in Amazonia. *Journal of Ecology*, *75*(2), 377–407. http://doi.org/10.2307/2260425.

**Analyze the Figure**

- What is the cumulative total of tree species found in the forest plots?
- Does the figure show the actual tree species richness of the forest? Explain your answer.
- What is your estimate of the tree species richness for trees in a site that was abandoned 5 years ago?

**Learning from the Case Study**

- Why is slash-and-burn agriculture unsustainable?
- How long do you predict it might take for diversity to return to the levels of the forest on an abandoned agricultural site? Explain your reasoning.

**Check Your Understanding**

- What is species richness?
- Is it possible to know exactly how many species live in an area? What factors would make a species difficult to find or identify?

## Biodiversity is a Function of Species Richness and Evenness

Species richness is an important variable, but is an incomplete measure of the diversity in a community. Some species may be common, while others are rare. The number of individuals in a species is the **abundance** of the species. The abundance of one species divided by the total number of individuals in all species is the **proportional abundance**. For example, suppose 500 trees were identified in a forest, and 400 of them were ponderosa pine, the proportional abundance of ponderosa pine would be 400/500 or 0.8 (Table 1). In this example, the tree community is made up of almost all one species. Other species may be represented by only a few individuals. The **evenness** of this community would be low because one species has a high proportional abundance.

Table 1. Hypothetical rank-abundance data for a community with 4 species and a total of 500 individuals. Species A dominates the community.

| Tree Species | Rank | Number of Individuals | Proportional Abundance |
|---|---|---|---|
| A | 1 | 400 | 0.8 |
| B | 2 | 50 | 0.1 |
| C | 3 | 40 | 0.08 |
| D | 4 | 10 | 0.02 |

A rank-abundance curve is a visual model for the evenness of species (Figure 6). The species (or other groups) are put in order from the most to the least abundant. The species with the highest proportional abundance has a rank of 1. The species with the second highest proportional abundance has a rank of two, and is plotted next, and so on. A steeper line indicates a lower evenness. The number of ranks tells you the species richness.

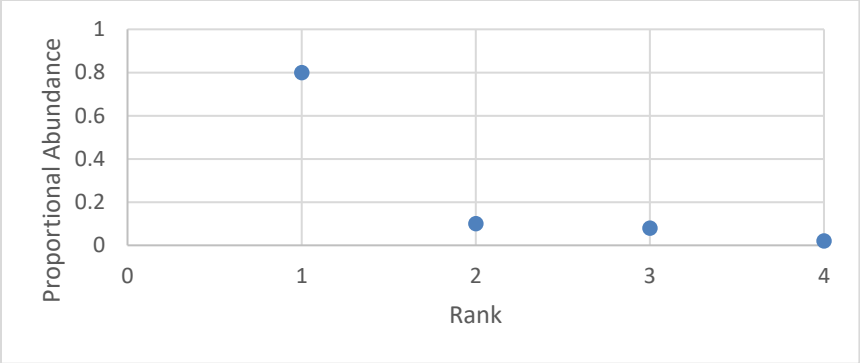



Figure 6. A rank-abundance curve for the hypothetical community in Table 1.

Comparing different communities on the same graph makes it easy to compare the evenness of different communities. Often ecologists are interested in which habitats or management strategies lead to which levels of richness and evenness. Site managers trying to restore longleaf pine forests in north Florida, US studied how different types of ground cover influenced the evenness of ant species (Figure 7).

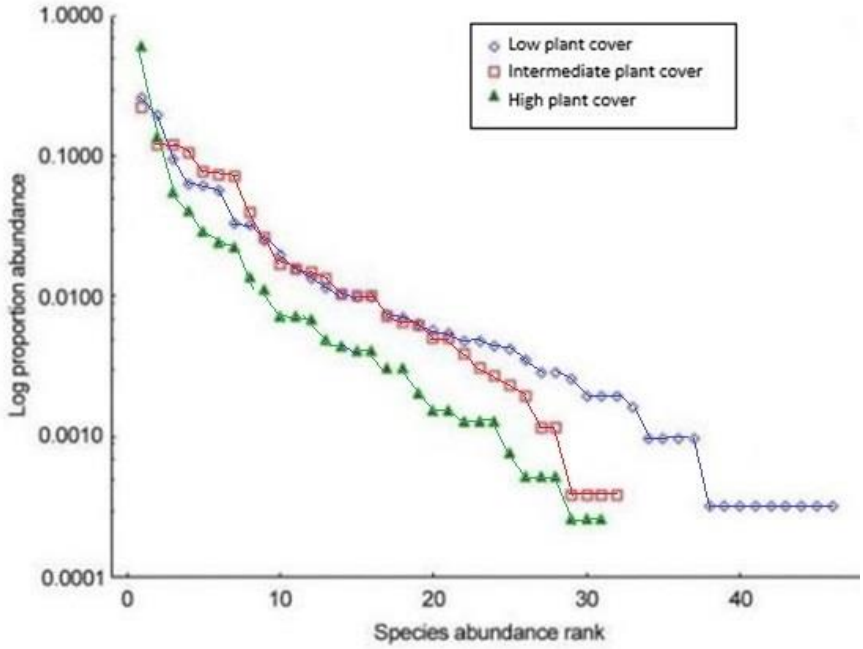



Figure 7. Rank-abundance curves of ant species in the longleaf pine forests in habitats with different levels of plant cover. The Y-axis is a log scale. This makes it possible to see differences in abundance between the rare species. Modified from: Lubertazzi, D. & Tschinkel, W.R. (2003). Ant community change across a ground vegetation gradient in north Florida's longleaf pine flatwoods. *Journal of Insect Science*, *3*.

**Analyze the Figure**

- What is the richness of ant species for each of the habitats?
- Which habitat has the lowest evenness of ant species?

The Shannon-Weiner diversity index condenses the richness and evenness measures of a community into one number, which is written as H' (H prime). This number is always positive. A higher number indicates a community with higher diversity. Because H’ is a function of both richness and evenness, it is possible for two communities to have the same H’ value, if one has a higher evenness and the other has a higher richness. For more on this topic, see **Model Skill: Calculating Shannon-Wiener Index of Diversity**

**Check Your Understanding**

- What is species evenness?
- What is the relationship between proportional abundance and evenness?
- How would increases in richness and evenness influence H'?
- How might increasing richness lead to decreasing evenness?

**Model Skill: Calculating Shannon-Wiener Index of Diversity**

The Shannon-Wiener diversity index is calculated as:

$$H' = -\sum_{i=1}^{s} p_i log_e p_i$$

Where H' = The Shannon-Wiener index of diversity
*s* = Number of species in a community
$p_i$ = Proportional abundance of *i*th species

As noted earlier, H' may only relate to a subset of taxonomic groups in a community (such as only the ants). Assume that "all" and "community" relate only to that subset. For each species in the community of interest, calculate its proportional abundance in the community, then get the natural log of that number, and multiply the natural log of the proportional abundance by the proportional abundance. Once you have done this for each species, add them all up and take the absolute value (make the number positive).

Calculate the Shannon-Wiener diversity index for Community X in Table 2. The first column in the table is a list of species. Letters have been used in place of names. The next column is the number of individuals in each species. For example, there are 5 individuals of species B. To get proportional abundance of species, divide the number of individuals in a species by the total number of individuals of all species. The natural log of the proportion is written as ln(proportion). To get the value for column 5 for each species, multiply the numbers from columns 3 and 4. One line has been completed for you. Use it to check your work.

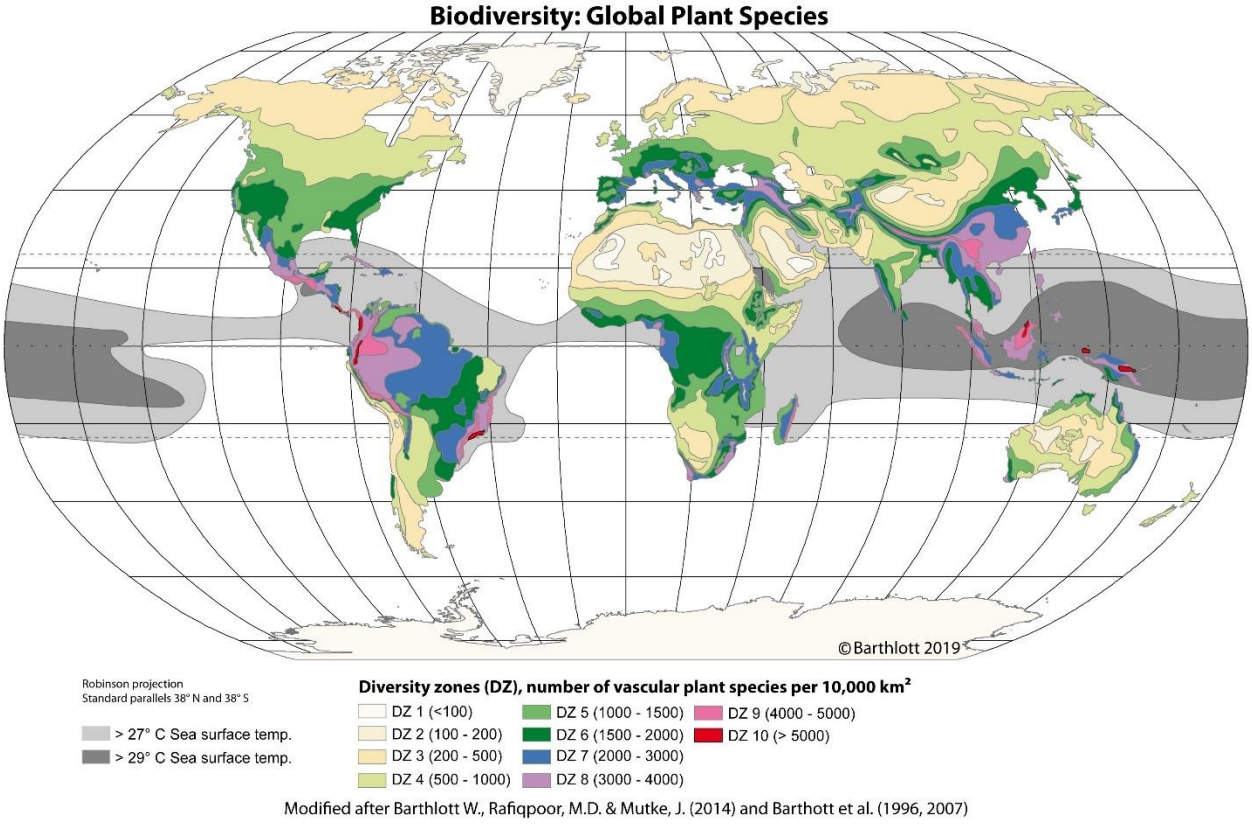
Table 2. Abundance of species in Community X.

| **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|
| Species | Number of individuals | Proportional abundance *Divide column 2 by the sum of column 2* | ln(proportional abundance) *Natural log of column 3* | Proportional abundance* (ln(proportional abundance)) *Multiply column 3 and column 4* |
| A | 10 | 0.5 | -0.693 | -0.347 |
| B | 5 | | | |
| C | 2 | | | |
| D | 2 | | | |
| E | 1 | | | |
| **Sum** | | Should = 1 | Do not sum | |

H' is the absolute value of the sum of column 5. **H'=**

## Diversity Varies by Biome

Why are tropical rainforests hot spots of biodiversity? Worldwide patterns of diversity (Figure 8) show that harsh climates—such as deserts and polar regions—tend to have low biodiversity, while areas with less extreme cold and dryness—such as rainforests—have high biodiversity. One hypothesis is that high productivity leads to high biodiversity. Ample water and sunlight generally lead to more photosynthesis. Areas with high productivity can support more individuals per unit area or volume. A poor environment may not support the minimum population size of some species. Another possibility is that few species evolve the traits needed to survive in harsh environments. Global biodiversity patterns could result from multiple factors.




https://commons.wikimedia.org/wiki/File:World_Map_Biodiversity_of_Plants_%28grids%29_%282%29_%C2%A9_W._Barthlott,_Lotus-Salvinia.de.jpg

Figure 8. Plant richness patterns. Compare this to the map of biomes (Figure 3) in Chapter 8.

### Analyze the Figure

- Which seems to have a greater influence on plant diversity, latitude or longitude?
- Describe patterns you observe about global position and biodiversity. You may want to discuss proximity to water, mountain ranges, or size of an area.

What other factors might lead to global patterns of biodiversity? Researchers created a model using just a few variables and were able to predict about 80% of the variation in diversity for terrestrial vertebrates (Figure 9). The key predictors of high biodiversity were warm, productive climate, a long time available for local evolution, and larger total area. For example, the high diversity of tropical rainforests is predicted because they receive a lot of sunlight and water, so their productivity is high (see Chapter 8, Figure 4). They cover a lot of Earth's surface. They are also an ancient biome, having been around for much longer than boreal forests or deserts. Evolutionary time allows for more speciation, producing **endemic species**, which are found only in that area. More evolutionary time also allows more time for extinction, but as species become better adapted to a biome, these losses would be expected to decrease.

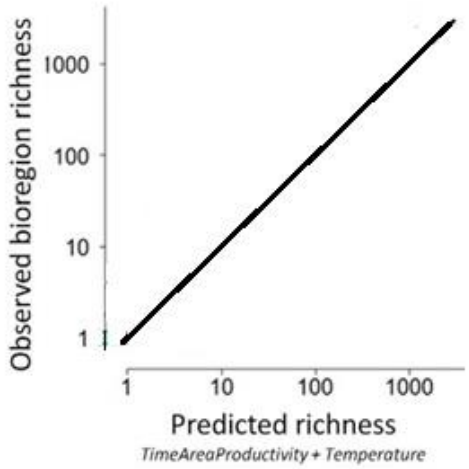



Figure 9. Richness as predicted by model that uses length of time for local evolution, size of an area, productivity and temperature compared to actual richness. Greatly simplified from: Jetz, W., & Fine, P.V. (2012). Global gradients in vertebrate diversity predicted by historical area-productivity dynamics and contemporary environment. *PLoS biology*, *10*(3), e1001292.

**Analyze the Figure**

- How well does the model (*TimeAreaProductivity* + *Temperature*) predict bioregion richness? Support your answer with evidence.
- Why do you think the scales are log-log?

**Check Your Understanding**

- Explain how productivity relates to biodiversity.
- Why would larger area have greater biodiversity?
- How might the harshness of a climate limit biodiversity?

**Patchiness Influences Diversity**

Another important factor in diversity may be whether an area contains many types of habitats. An area that is **heterogeneous** has many patches that are different from each other. An area

that is **homogeneous** is all fairly similar. A more heterogeneous environment might support a greater range of species because different species can specialize in different habitat types (see Chapter 14). When the area is homogeneous, there may not be patches that are suitable for all potential new species. However, if there are many patches in an area, each patch suitable for a particular species must be smaller. The small area supports fewer individuals of that species (abundance is lower), so the risk of extinction due to random (stochastic) events is high. This tradeoff between patch variety and patch size suggest that there will be an optimal value of heterogeneity somewhere between the extremes (Figure 10). The study of heterogeneity and landscape patterns will be discussed further in Chapter 18.

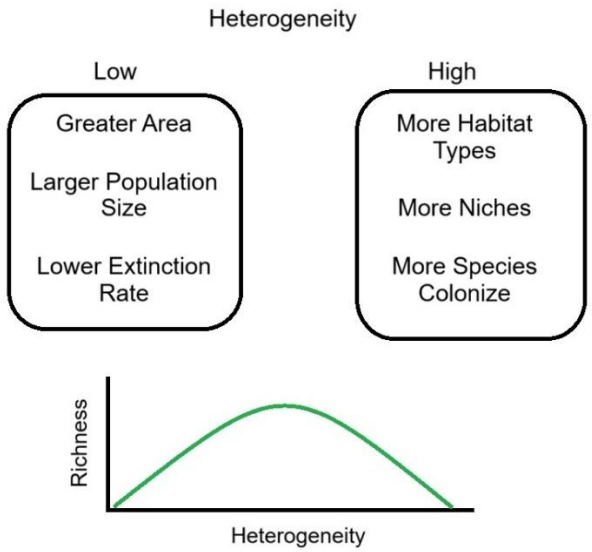



Figure 10. A model of species diversity as a function of heterogeneity (patchiness).
Modified from: Allouche, O., Kalyuzhny, M., Moreno-Rueda, G., Pizarro, M., & Kadmon, R.. (2012). Area-heterogeneity tradeoff and the diversity of ecological communities. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(43), 17495–17500.

**Analyze the Figure**

- According to the model, what limits populations when heterogeneity is low?
- According to the model, what limits populations when heterogeneity is high?
- In actual communities, would you predict that the highest value for species richness would always be halfway between the extremes? Explain your reasoning.

Disturbances that create patches with different successional stages can create heterogeneity. Succession itself influences biodiversity. In early stages of succession, diversity may be low because only the hardiest plants can grow in the newly-opened habitat. In the climax stage, only a few successful competitors may remain. would have patches that supported species specializing in different successional stages. The intermediate disturbance hypothesis predicts the highest diversity in communities with occasional, localized, or mild disturbances.

**Hypothesis Testing: Does Habitat Diversity Increase Overall Diversity?**

https://commons.wikimedia.org/wiki/File:Great_barrier_reef.JPG

Figure 11. Coral in the Great Barrier Reef, Australia.

Some taxonomic groups provide both habitat structure and food for other species in the community. For example, trees in a forest, kelp near shorelines, and grasses in a prairie provide both resources. Several experiments have shown that diversity in these habitat-creating taxonomic groups lead to a higher overall diversity in their communities. Messmer et al. (2011) studied diversity in coral reef communities (Figure 11) in the waters near Lizard Island in Australia's Great Barrier Reef and Schumann Island in Papua New Guinea's Kimbe Bay. They investigated whether increasing coral species richness increased fish species richness, evenness, and abundance. They tested three hypothesis about the mechanisms that might cause increasing fish diversity with increasing coral diversity:

1. Increases in fish species diversity are the result of increasing habitat diversity providing more types of spaces for shelter (habitat structure).
2. Different fish species depend on different coral species for food (niche partitioning).
3. The environment causes both coral diversity and fish diversity.

Researchers constructed 45 artificial reefs using live coral. The reefs were built on sand in shallow water with no reefs (artificial or natural) within 15 m. Low diversity reefs were constructed using one coral species per reef. The medium diversity plots contained 3 species, and the high diversity reefs contained 6 coral species each. The species used were varied systematically. Researchers then measured fish species richness, evenness, and abundance of individual fish within taxonomic groups (Figure 12).

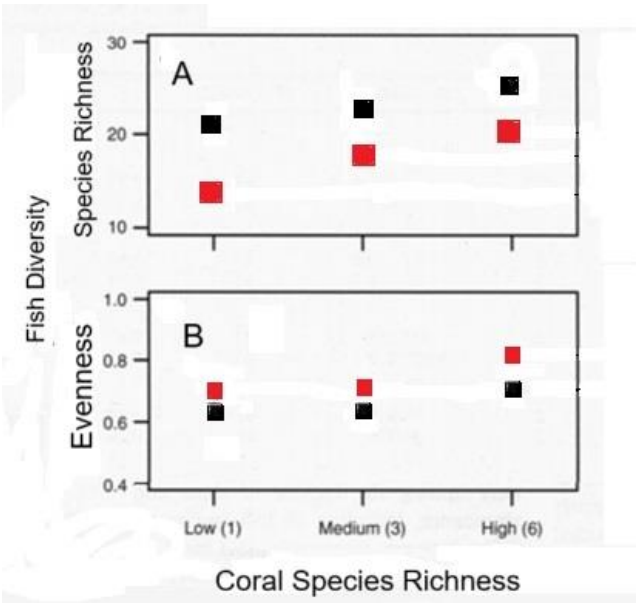



Figure 12. Influence of coral species richness on fish diversity. Black squares represent Lizard Island. Red squares represent Kimbe Bay. Modified from: Messmer, V., Jones, G. P., Munday, P. L., Holbrook, S. J., Schmitt, R. J., & Brooks, A. J. (2011). Habitat biodiversity as a determinant of fish community structure on coral reefs. *Ecology*, *92*(12), 2285-2298.

**Analyze the Figure**

- Did areas with greater coral species richness have higher fish species richness?
- Did areas with greater coral species richness have higher fish species evenness?
- Which treatment (coral richness) would have the highest H' for fish?

The researchers had controlled for environmental variability by constructing the artificial reefs at random locations. Therefore, the reef diversity was not the result of underlying differences in environmental variability. Further analysis of the data showed that different coral species led to differences in species richness. Some artificial reefs containing only one coral species had as many species as the reefs with six different coral species.

**Evaluate the Hypotheses**

Which hypotheses are supported by the data? Explain your reasoning.

1. Increases in fish species diversity are the result of increasing habitat diversity providing more types of spaces for shelter (niche partitioning due to habitat structure).
2. Different fish species depend on different coral species for food (niche partitioning due to food specialization).
3. The environment causes the patterns both coral diversity and fish diversity (coral diversity itself does not cause the diversity).

Is it possible to eliminate any of the hypotheses based on the findings of this study? Is it possible that more than one of these hypotheses are supported by the data provided? What additional data might allow you to evaluate these hypotheses more fully?

**Check Your Understanding**

- What is heterogeneity? Give an example that is different from those discussed so far.
- How might heterogeneity influence species richness? Discuss the effect of different levels of heterogeneity.

**Biodiversity Influences Productivity**

As mentioned earlier, biomes with higher productivity tend to support communities with high biodiversity. A community with high biodiversity may also have a higher productivity then a less diverse community with the same amount of sunlight and water. A diverse community will have species with different strategies for using resources. For example, a high diversity forest will have trees and understory plants of different heights and shapes, potentially capturing more of the available sunlight than a forest of low diversity. A patch of soil that is not suitable for one species may support dense growth of another. Productivity on higher trophic levels will depend on primary productivity and the ability of organisms at higher trophic levels to use the producer species. In a community with low diversity, some resources may go unused because there are no species that use them effectively. This will reduce overall productivity.

Separating causes and effects of biodiversity and productivity requires controlled experiments. Researchers analyzed the results of multiple different experiments over several years that manipulated several potential drivers of productivity in upland grasslands (Figure 13). Treatments included increasing species diversity (from 1 to 16 species, from 2 to 16 species, and 4 to 16 species), adding nitrogen at 3 different levels, adding or withholding water (and the effect of a natural drought), adding $CO_2$, removing deer and insect herbivory, or changing fire treatments.

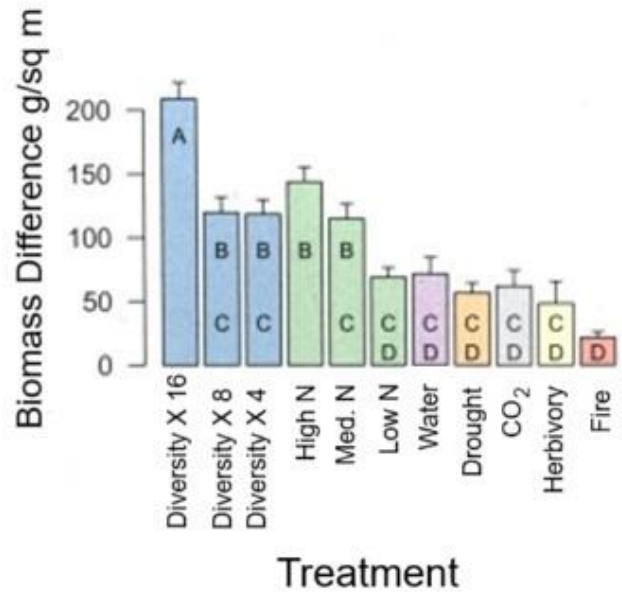



Figure 13. Biomass difference between treatments and control plots in grasslands. Different letters show significant differences between treatments.
Modified from: Tilman, D., Reich, P. B., & Isbell, F. (2012). Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. *Proceedings of the National Academy of Sciences*, *109*(26), 10394-10397.

**Analyze the Figure**

- Which factors apparently caused the greatest biomass increases?
- Did the increase from 2 to 16 species result in greater biomass than increasing diversity from 4 to 16 species?
- All 3 nitrogen treatments were additions. Did larger additions result in significant increases in biomass?

**Check Your Understanding**

- Why might increasing diversity lead to higher productivity?
- Would this effect be the same in different biomes? Explain your reasoning.

**Human Actions Threaten Biodiversity**

The greatest threat to biodiversity is habitat destruction. As human convert ecosystems for agriculture, housing, or extracting resources (timber, minerals, etc.), species are lost. A common saying in the conservation community is “save the habitat, save the species.” Climate change threatens habitats all over Earth. For a long-term view of global extinction, see **Evolutionary Perspective: Patterns of Diversity in Evolutionary Time**.

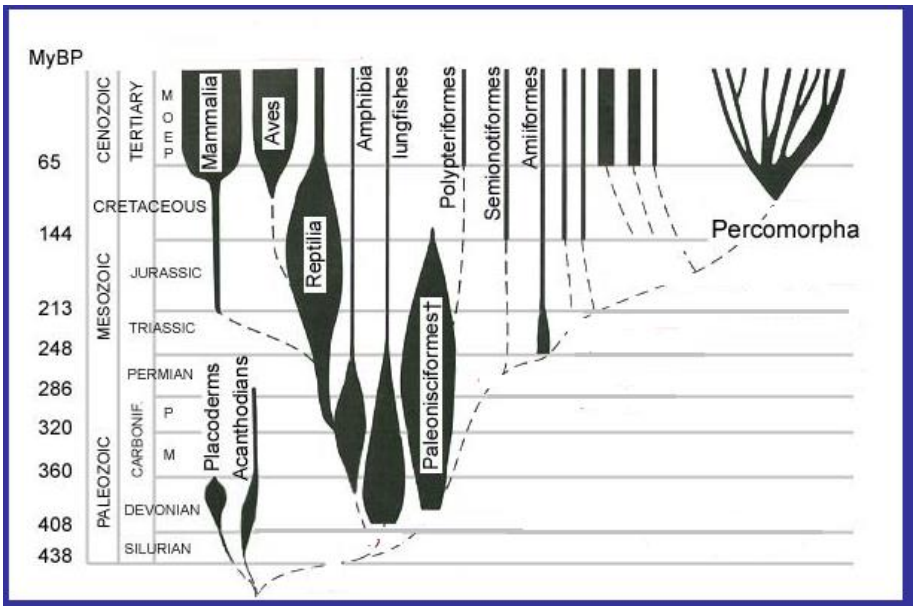
Endemic species are often at great risk for extinction because there are no other populations replenish an area. Old islands may have multiple endemic species because species have had a long time to evolve in isolation, but any area may have endemic species.

Toxins in the environment can poison species. Human activities introduce toxins into the air, soil, and water. As discussed in Chapter 5, toxins tend to get more concentrated in higher trophic levels. There is growing concern about drugs such as hormones and antibiotics entering natural water systems. These drugs may be responsible for abnormal development in aquatic species.

Overexploitation of species is another cause of extinction. Developed countries generally use regulation to preserve their populations of certain vulnerable species. Developing nations may lack the resources or stability needed to effectively protect threatened species. They may have difficulty meeting the needs of their citizens and view protection of non-humans as a low priority. People in dire poverty may be desperate enough to risk death in order to harvest valuable plants or animals. Large mammals and birds tend to have more advocates than smaller, less photogenic species.

Adding or removing a single species can severely reduce biodiversity in a community. When a new species is introduced to a community, it may die off, persist in low numbers, or become an **invasive species** that disrupts the community by outcompeting, preying on, or otherwise inhibiting native species. Native species may not have not evolved traits that allow them to compete with, or defend themselves against the introduced species.

**Evolutionary Perspective: Patterns of Diversity in Evolutionary Time**




Adapted from: http://www.mudskipper.it/SysEvol.html

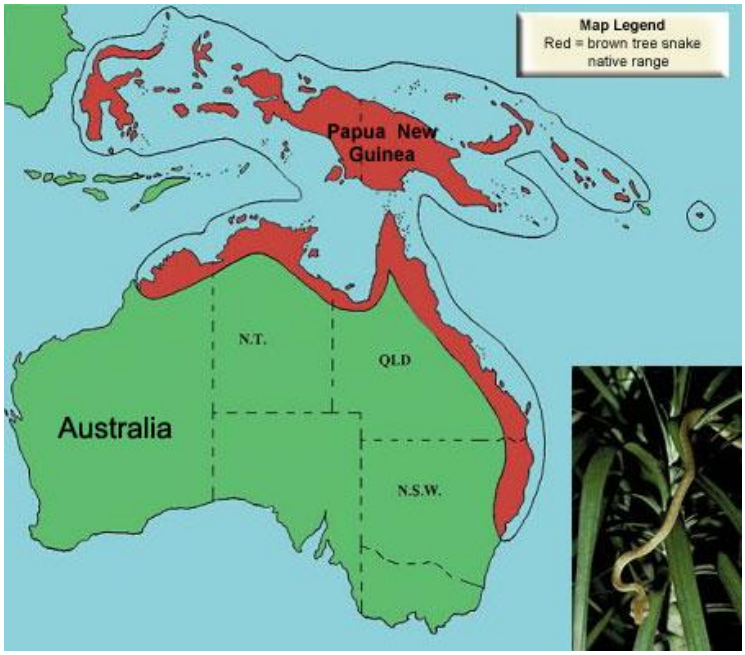
Figure 14. Vertebrate diversity as shown by the fossil record. Width of lines indicates number of species. MyBP = million years before present.

The diversity of various groups has changed drastically over evolutionary time. Vertebrates have been around for over 500 million years (Figure 14). During the Devonian Period (about 400 million years ago), there were thousands of placoderm fish species, but they became extinct. Dinosaur diversity was high during the Jurassic and Cretaceous periods, as shown by the width of the Reptilia line. Today, the dinosaurs are only represented by the thousands of bird species that evolved from them.

What causes changes in diversity over long periods of time? The mechanisms are the same as those we see today. They include environmental change, competition, predation, pathogens, lack of resources, and other causes. In ecological time, species interactions can change when species move into or out of an area. Over evolutionary time, entire new types of organism can evolve. If the new species have traits that are significantly better than the traits of existing organisms, they can diverge into many more new species. For example, amphibians usually need wet environments, especially for breeding. When reptiles evolved waterproof scales, shelled eggs, and other traits that allowed them to live far from water, they were able to invade new habitats. Many new reptile species evolved, and some may have outcompeted amphibians.

Species can be introduced intentionally or unintentionally. For example, rabbits were introduced to Australia to provide hunting opportunities. They multiplied quickly and consumed so much of the native vegetation that a disease was introduced to reduce the population. Both of these introductions (the rabbits and the disease) were intentional.

Brown treesnakes were introduced to the island of Guam unintentionally after World War II. They were probably in cargo shipped from their native habitat in and around Papua New Guinea (Figure 15). The snakes left behind their natural enemies, and the birds in Guam had no defenses against tree-climbing snakes. The snakes are nocturnal, so they received little notice as their population expanded. By the 1960's they had become very common. As discussed in Chapter 14, keystone species can disrupt communities even when their numbers are small. The snakes caused power outages by climbing onto high-voltage transformers, invaded homes, and permanently changed the island's biodiversity. The snakes wiped out most of the resident vertebrates. At least 12 species of birds were permanently lost from Guam. Some of those species were endemic.




http://www.fort.usgs.gov/resources/education/bts/bioeco/btsnake.asp

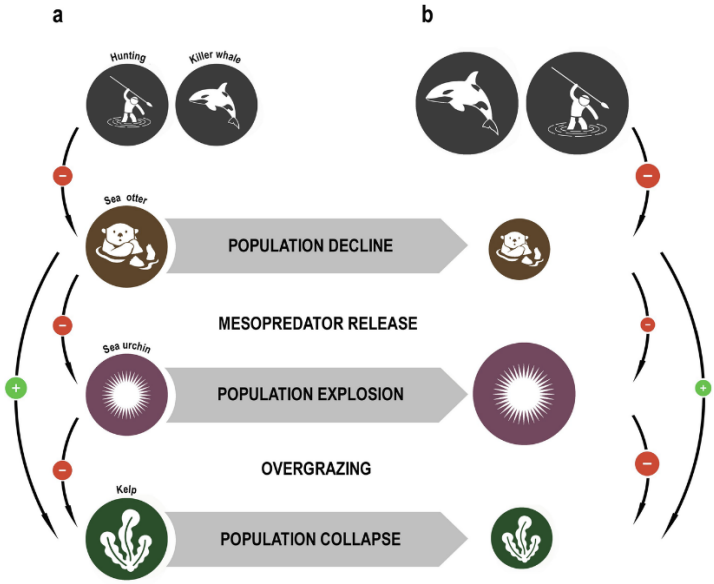
Figure 15. Native range of the brown treesnake (*Boiga irregularis*). Guam is over 2,000 km north of the snake's native range.

Today, special dogs are used on Guam to sniff outgoing cargo for brown tree snakes. Several islands have already been invaded, but officials hope to protect other islands. The government has also started lacing dead mice with acetaminophen, attaching cardboard parachutes, and dropping them into the forest from helicopters. The painkiller is lethal to brown tree snakes. This program will not eliminate the snakes but may help to reduce their numbers. Currently the brown tree snake population on Guam is declining, perhaps because they have reached carrying capacity of the island (see Chapter 12).

https://commons.wikimedia.org/wiki/File:Helicopter_distributing_aerial_mouse_baits_USDA_%289601697356%29.jpg

Figure 16. Helicopter over Guam dropping acetaminophen-laced dead mice with tiny parachutes (lower right) to poison brown treesnakes.

The effect of species loss on community stability may depend on how diverse the community is to begin with, how many functionally equivalent species are available, and whether the loss is to a keystone species. Removing a single keystone species can cause trophic cascades (see Chapter 14). Sea otters are keystone species in kelp forests (Figure 17). Sea otters mainly eat sea urchins but also eat some other invertebrates and fish. Fur hunting wiped out many sea otter populations on the Pacific Coast of the United States by the early 1900s. When sea otters are removed from these coastal communities, the only predators for sea urchin are sea stars (starfish). The sea urchin populations soar and they eat most of the kelp and other large algae. This leaves little food for other species and results in a major loss of diversity. Sea otters are now protected from hunting, but they have become a favored prey of orcas (killer whales).




https://commons.wikimedia.org/wiki/File:Changes_in_abundance_in_a_temperate_rocky_reef_ecosystem.png

Figure 17. Model of how sea otter numbers influence kelp forest communities.

**Analyze the Figure:**

- How does orca population size influence sea otter numbers?
- How do sea otter numbers influence kelp?

Large predators are often keystone species. These predators have often been killed in order to protect game animals, livestock or people. This has led to fast growth of herbivore populations, over-consumption of plants, and a decrease in the carrying capacity of many habitats (see Chapter 11). Reintroduction of keystone predators is still controversial.

**Misconception Alert: Extinction is not a problem because it is balanced by evolution of new species.**

**FALSE.** Human activities have greatly increased the rate of extinction. While 90% of species that have ever existed are now extinct, life has been on Earth for about 3.5 billion years. Natural rates of extinction rise and fall due to phenomena such as climate changes. Some estimate that the current rate of bird extinction is 100 times the rate before Europeans started travelling the globe in about 1500. Since then about 150 species of birds may have gone extinct. New species, particularly vertebrates, usually take a long time to evolve. It is unlikely that any new bird species have evolved in the past 500 years.

**Case Study Part 3: Maintaining Tropical Diversity Using Traditional Ecological Knowledge**

https://commons.wikimedia.org/wiki/File:Las_Nubes_Chiapas_-_panoramio.jpg

Figure 18. Rainforest in Chiapas, Mexico.

As discussed in Chapter 16, disturbances change communities. It will take many years for an abandoned agricultural field to become a mature rainforest again. However, some management and restoration strategies may help to increase biodiversity. The Lacandon Maya people of Chiapas, Mexico have been using rainforests for agriculture for generations while maintaining the overall biodiversity of the lands they manage. The community uses forest plants for food,

fuel, medicine, building materials, and other purposes. Cultivating forests for resources is called agroforestry.

The Lacandon Maya use fire as a management tool and use some plant species strategically to improve soil nutrients and organic matter. They rotate their land use so that different areas are in different successional stages. The successional stages increase in diversity (Figure 19). They also keep a portion as primary (old growth) forest. Traditional ecological knowledge (TEK) can be used to develop sustainable agroforestry that protects the forest ecosystem and the people who depend on it. In contrast, other lands in the Chiapas region do not use traditional agroforestry practices and are used for short-term agriculture and cattle ranching. The damage to the soil leads to species-poor grass and brush communities that do not progress toward old growth rainforest. The degraded land provides little benefit to people and contributes to loss of species.

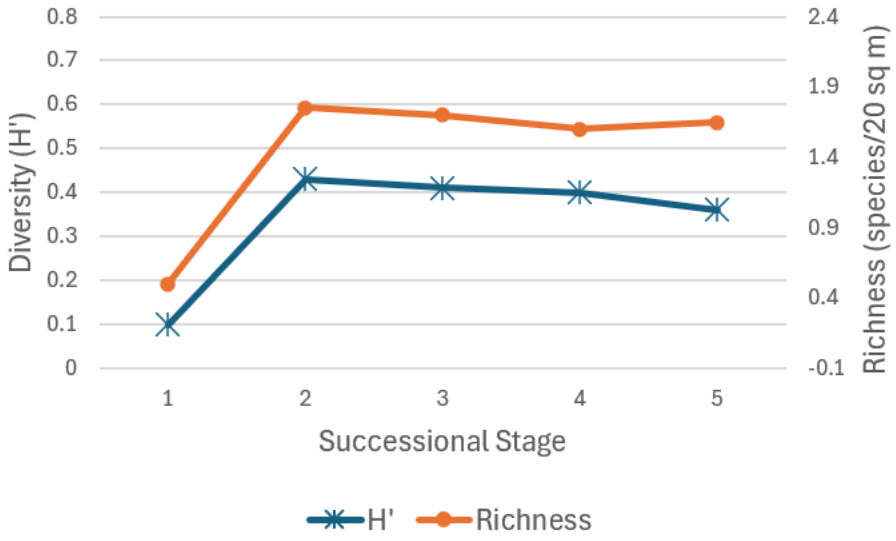



Figure 19. Mean H' and species richness over successional stages in tropical rainforest areas managed by the Lacandon Maya. Stage 1 is mainly forbs. Stages 2 and 3 are shrub-dominated. Stages 4 and 5 are forests that have diversity similar to that of old growth forest. Modified from: Diemont, S. A. W., & Martin, J. F.. (2009). Lacandon Maya Ecosystem Management: Sustainable Design for Subsistence and Environmental Restoration. *Ecological Applications*,*19*(1), 254–266.

**Analyze the Figure**

- How does biodiversity (H') change over time?
- Are changes in H' similar to the changes in species richness?

Other management practices can also be used to restore abandoned agricultural fields. Old growth species can be planted as seeds or young plants. These practices can "fast-forward" through successional stages, preventing pioneer species from dominating the abandoned fields. The mature plants provide habitat for seeds in the soil to sprout and attract animals that can

carry more seeds. Studies around the world have found that agroforests maintain fairly high levels of animal biodiversity.

**Learning from the Case Study**

- Can disturbance be used strategically to maintain biodiversity while supporting human populations? Explain your reasoning.
- Would the same practices be necessary or beneficial in other biomes? How might they need to be adapted?

**Taking It Further: Abundance Can Distort Diversity Measures**

Data-driven management decisions often require **meta-analysis** of the results of multiple studies rather than conducting new experiments. For example, some researchers were interested in whether organic farming or fire-based wildland management helped to conserve diversity. The researchers analyzed changes in richness, evenness, and species abundance in hundreds of published studies involving changes in management practices.

Recall from the species-effort curves earlier in this chapter that greater sampling efforts or density of individuals will likely lead to finding more rare species. Imagine that you were collecting insects at two sites. Some insect species are very rare. If you collected 100 individual insects from each site, and the species richness was higher in the sample from site A, this would be evidence that site A had a greater total richness (not just a greater richness in your sample).

If the insect abundance were 10 times higher at site A, and you surveyed equal areas, you might get 10 times more individuals at site A. What if your samples had 1000 individual insects from site A and 100 from site B? You would expect to find more rare insects in the larger sample, even if the actual richness of both populations were the same. For example, perhaps only 1 individual in 500 is species X. A sample of 100 individuals is unlikely to include it. A sample of 1000 is likely to include it.

To correct for the problem of unequal samples, you could randomly draw 100 insects from your 1000-insect sample at site A and compare that with your sample from site B. This would be a process called **rarefaction**. Rarefaction allows a fair comparison of species richness between samples of different size or communities with different abundance levels.

**Check Your Understanding**

Describe some ways that human activities threaten biodiversity.

- What practices might be used to conserve or promote biodiversity?
- How might adding a species to a community decrease community diversity?

# Key Concepts

- Biodiversity is a measure of the variety of organisms in an area. Diversity is a function of species richness and evenness.
- The total number of species in unknown. Large, common species in well-studied areas are most likely to have been cataloged.
- Biodiversity varies due to many factors such as productivity, landscape patterns, and time for speciation.
- Habitat loss, species introduction, over-exploitation, and toxins threaten biodiversity.
- Keystone species have a disproportionate influence on diversity.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately analyze patterns of diversity*
2. *Draw reasonable conclusions about extinction risks*
3. *Evaluate consequences of changes in biodiversity*

1. Refer to Figure 20.

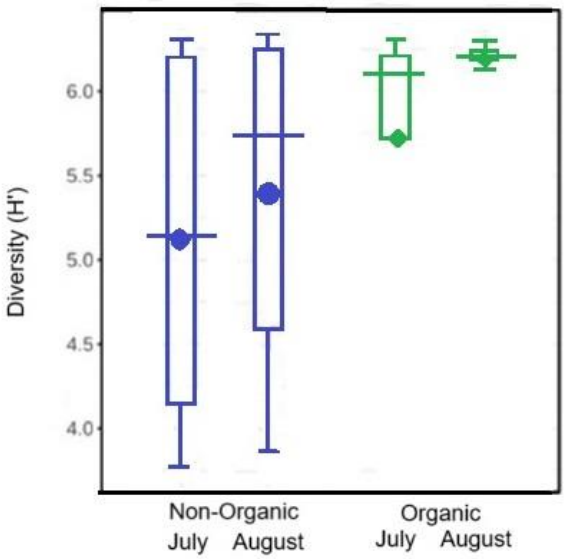
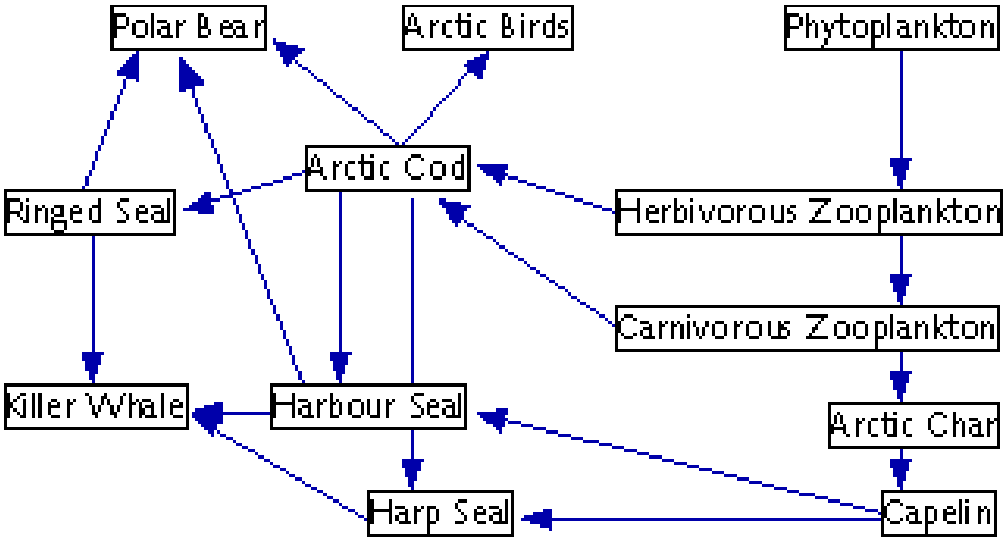



Figure 20. Microbial diversity in soil from non-organic and organic fields after 10 years of pasture management. Central lines are medians. Markers are means.
Acharya, Modified from: M., Ashworth, A. J., Yang, Y., Burke, J. M., Lee, J. A., & Sharma Acharya, R. (2021). Soil microbial diversity in organic and non-organic pasture systems. *PeerJ*, *9*, e11184. https://doi.org/10.7717/peerj.11184.

A. Which treatment resulted in the highest median diversity? *(Learning Outcome 1)*
B. Which treatment had the most variation in diversity? What cause that variation? *(Learning Outcome 1)*
C. Which treatment is likely to lead to loss of microbial species? *(Learning Outcome 2)*

2. Refer to Figure 21.

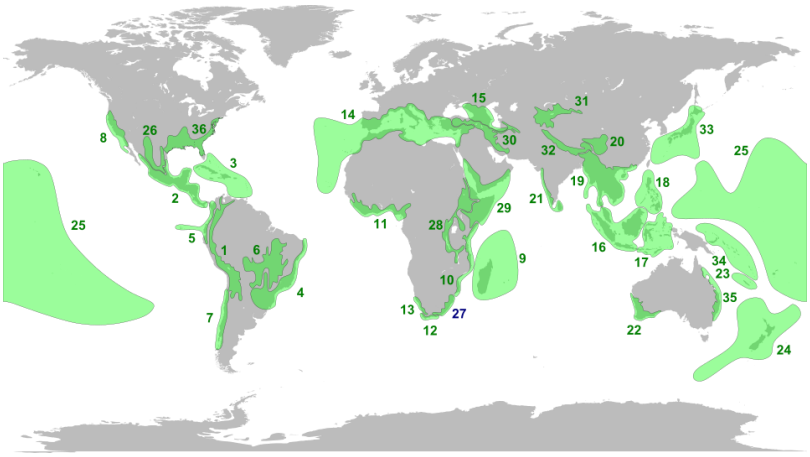



http://commons.wikimedia.org/wiki/File:Foodweb.png

Figure 21. Arctic food web. Ignore the position of the species, but note the direction of the arrows.

A. Which species in the Arctic food web is likely to be a keystone species? Explain your answer. *(Learning Outcome 1)*
B. If Arctic cod were to disappear from the Arctic ecosystem, what changes might you see in other species? Predict which populations would increase or decrease and explain your reasoning. *(Learning Outcome 2)*
*C.* The "phytoplankton" box actually contains many species. What would happen to the stability of the community if there were only one or two species of phytoplankton. Explain your prediction. *(Learning Outcome 3)*

3. Refer to figure 22.




https://commons.m.wikimedia.org/wiki/File:Biodiversity_Hotspots_2015.svg

Figure 22. Biodiversity hotspots. Numbers identify the areas.

A. Select some hotspots by number and explain geographic factors that might cause increased diversity. *(Learning Outcome 1)*
B. Rising sea levels could threaten coastal areas. Explain how the loss of hotspots would influence global biodiversity. *(Learning Outcome 2)*

4. Calculate the Shannon-Weiner diversity index (H') for the community in Table 3.

Table 3. Abundance of species for Community Y. Some values have been filled in to allow you to check your work.

| Species | Number of individuals | Proportional abundance | ln(proportional abundance) | Proportional abundance* (ln(proportional abundance)) |
|---|---|---|---|---|
| 1 | 8 | | | |
| 2 | 6 | | | |
| 3 | 6 | 0.250 | -1.368 | -0.347 |
| 4 | 3 | | | |
| 5 | 1 | | | |
| **Sum** | | Should = 1 | Do not sum | |

**H'=**

A. Compare Community X (page 7) to Community Y. Which community has greater richness?
B. Which community has greater evenness?
C. Which community is more diverse?
*(Learning Outcome 1)*

# Unit VI

# The Larger Picture

Burton 2013

Human impacts on the landscape in Wisconsin, USA.

**Scale and pattern are important in understanding ecological processes.**
**Environmental issues can be influenced by changing human behavior.**

### Unit Outcomes

- Clearly explain how spatial scales influence ecological phenomena such as biodiversity and productivity
- Draw reasonable conclusions about how economic factors and political power influence environmental practices
- Effectively analyze efforts to change human behaviors related to environmental issues

**Unit VI: The Larger Picture**

# Chapter 18: Scale and Pattern

## Case Study Part 1. Designing a Landscape that Protects Species

https://en.wikipedia.org/wiki/Kelp_forest#/media/File:Diver_in_kelp_forest.jpg

Figure 1. California's coast includes many habitats, including highly productive kelp forests.

In 1999 California passed the Marine Life Protection Act, mandating that the state manage its marine resources sustainably using Marine Protected Areas (MPAs) where fishing was banned. The legislation was controversial. Would it destroy the livelihoods of many of its citizens? How much area could or should be set aside? Where should the MPAs be located? How big would the MPAs need to be? Would the plan even work? This chapter will explore how patterns in space, time, and organizational level are central to understanding and protecting ecosystems.

### Learning from the Case Study

- What stakeholders might be affected by the creation of MPAs? How?
- What information would help the natural resource managers make good decisions?

# Learning Outcomes

1. *Explain the importance of scales of time, space, and organization in the study of ecology*
2. *Apply landscape ecology concepts to issues of species conservation.*
3. *Accurately analyze processes behind global patterns such as weather, biodiversity, productivity, and movement.*

**Vocabulary Toolkit**

**Word Watch List**

**Emergent property**: Characteristic present at one level of organization, but not at a simpler level
**Landscape**: Area made of heterogeneous patches
**Island biogeography**: Study of population and community ecology on islands
**Habitat island**: Area of suitable habitat surrounded by unsuitable habitat
**Habitat fragmentation**: Process of dividing large areas of habitat into small patches
**Corridor**: Connectors between habitat patches that allow for travel
**Equilibrium**: Point in a model. After values change, they tend to return to this point
**GIS**: Global information system. Worldwide data set organized by its location
**Overlay**: Data set containing a specific type of information that can be related to a map
**Indicator**: Attribute used as a marker for a more complex variable, such as habitat quality
**Biosphere**: All the ecosystems on Earth
**Meta-population**: A group of populations that have effective genetic exchange

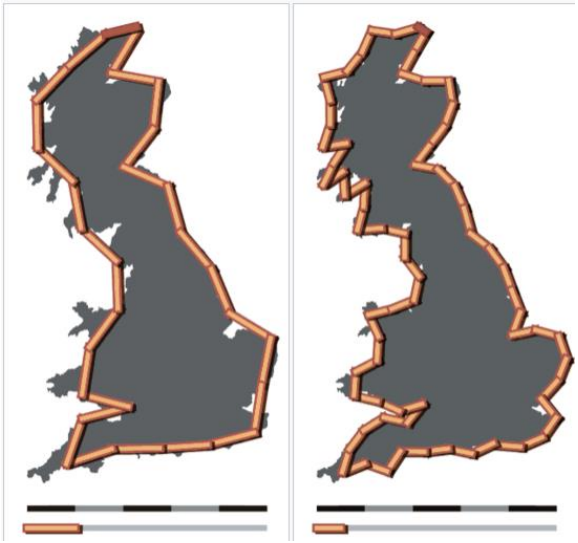
### Landscape Structure and Function Vary with Scale

Recall from Chapter 17 that landscapes are composed of patches. A heterogeneous landscape will have many different patches, while a homogeneous area will be similar all over. Patches can differ in many ways, including type of soil, habitat quality, or climate. Landscape ecology is a study of how and why patches on a landscape develop and interact.

Understanding landscape structure and function requires studying processes at appropriate scales of space (spatial scales), time (temporal scales), and organization (molecule to biosphere). Due in part to these differences in scale, living things do not all experience the world in the same way. For bacteria, your gut contains multiple ecosystems. A lifetime for a bacterium may pass while you are taking a nap. A major disturbance for an ant, such as catastrophic damage to an anthill, is just another footstep for an elephant. To understand forest fire dynamics at the landscape level, ecologists may have to study millions of hectares and information from centuries ago (such as historical climate data, patterns of species invasion, and human activity).

As humans, we tend to measure spatial and temporal scales by our own experience, but it is useful to remember that judgments such as “big” and “small” are subjective. A classic example

of the subjectivity of spatial scale is the measurement of a coastline. Measurement of length may seem like an objective value, but coastlines are complex. The size of our measurement unit will determine which curves are counted and which are not (Figure 2). For example, if you walk along an entire coastline as you experience it, your journey would be much shorter than the journey of a tiny insect, which experiences each pebble as a curve that adds to the distance. For bacteria settling on the coastline, each bump on the surface of a grain of sand adds to the length of the coastline.



https://en.wikipedia.org/wiki/Coastline_paradox

Figure 2. The effect of measuring a coastline using measuring sticks of different sizes. For an animation, see https://en.wikipedia.org/wiki/Coastline_paradox#/media/File:Great-britain-coastline-paradox.gif

**Analyze the Figure**

- As the measuring stick length decreases, what happens to the measurement of the coastline?
- How would this pattern relate to the scale of organisms and their environment?

Some properties can only be measured at particular scales of organization. For example, you can measure the age of a live tree or lifespan of a dead tree by looking at its rings. To get an average life expectancy, you would have to analyze data from a population of trees. This makes average life expectancy an **emergent property**. It only emerges when you study the population level of organization. Life is a property that emerges at the level of the cell. Genetic diversity (genetic variability between individuals) is only meaningful on the population level. Species richness is meaningless on the population level; it emerges at the community level. Nutrient cycling is meaningless at the community level because nutrients themselves are not organisms, and they often circulate through non-living pathways. It emerges at the ecosystem level. Some

patterns, such as ocean currents and major weather systems, only emerge at the global or biosphere level.

**Check Your Understanding**

- How might temporal and spatial scales be important in understanding the ecology of a soil microbe as compared to a tree?
- How does spatial scale influence measurement?
- What is an emergent property? Give your own example.

## Larger Habitat Islands Support Greater Biodiversity

Island biogeography is the study of how landscapes with patches of suitable and unsuitable habitat influence biodiversity. While the traditional definition of islands is small land masses surrounded by water, island biogeography is concerned with **habitat islands** (Figure 3). A city park may be a habitat island for oak trees surrounded by urban area. A lake is a habitat island for a lake trout. Landscape ecology is used to improve management decisions because protected areas are also types of habitat islands.

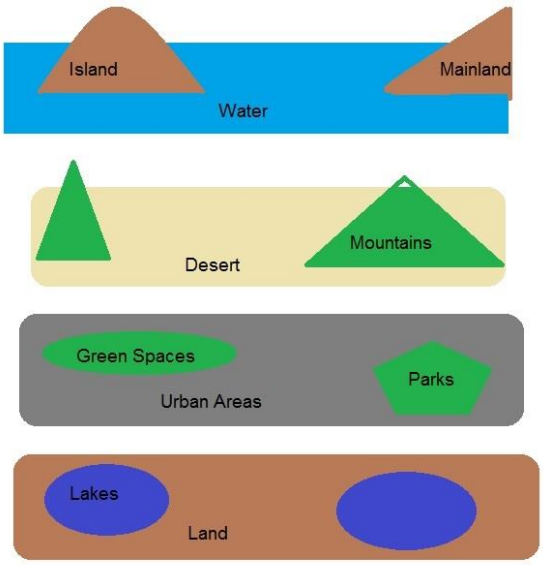
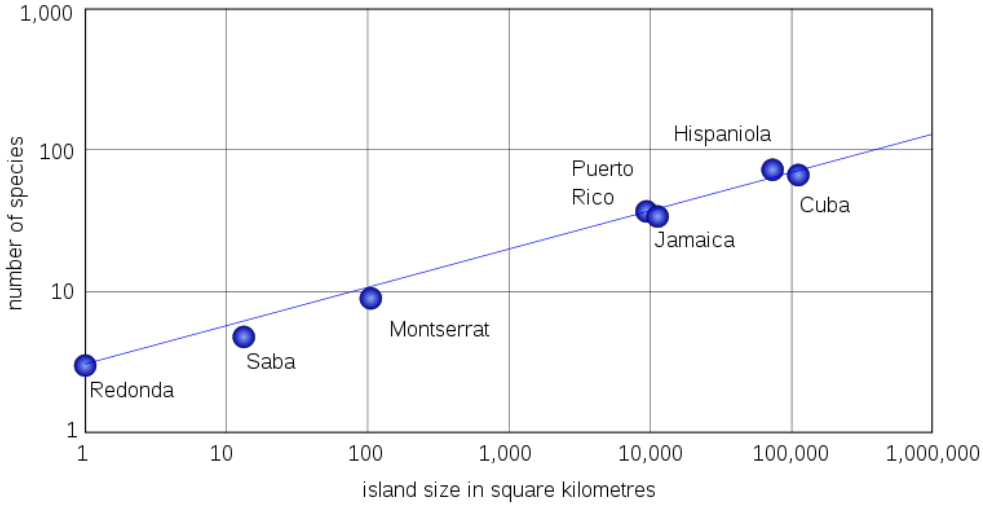



Figure 3. Examples of habitat islands.

Recall from Chapter 17 that as researchers look at larger or more patches of habitat, they tend to find more species (though new discoveries level off). A similar pattern is seen with habitat islands. Species richness is greater on larger islands (Figure 4). One reason is that a larger island may provide more resources. A smaller island may not provide enough resources to support a healthy population of a particular species. Recall from Chapter 17 that habitat diversity (heterogeneity) can increase biodiversity. A larger island may have more variety of habitats and other resources, allowing more different species to coexist. A larger island may

also provide a larger “target” for species arriving from the mainland. The comparisons between islands of different sizes make the most sense when comparing islands with similar climates. For example, a consistent pattern between size and biodiversity is likely for the different Channel Islands of California. Such a pattern might not exist if the Channel Islands and Alaska’s Aleutian Islands were part of the same model.




http://commons.wikimedia.org/wiki/File:Area_species_curve_herpetofauna.svg

Figure 4. Number of reptile and amphibian species on various sizes of islands in the West Indies in the 1950’s. Note the log-log scale.

**Model Skill: Variables and Constants in the Species Area Equation**

Figure 4 shows the relationship between island size and the number of species on an island. The line that would describe the relationship best would be the model of the relationship. It can be written as an equation:

$$S = C A^z$$

**A** (area) is an independent variable. It can have as many possible values as there are sizes of islands. The number of species on the island will not change the island's size.

**S** (species richness) is the dependent variable. Its value will depend on A, C, and z.

**C** is a constant. It accounts for the differences between species. You would expect to find many more insect species than amphibian species on a given size of island, so C is different depending on the taxonomic group, but does not vary with island size. It is larger for animals that are smaller and travel between islands easily. It is smaller for large animals and those with less mobility. Researchers look at the actual data for any taxonomic group to find a value for C.

**z** is also a constant. It is usually 0.3 for habitat islands. A different value for z might be used depending on how accessible the islands are, or how many habitat types they provide. Because accessibility depends on the mobility of the species, z might be higher for more mobile taxa. Researchers look at the actual data for any type of island and taxon to find a value for z.

Figure 4 uses log scales for both axes. Each step on the axis shows a 10-fold increase. This produces a straight line. Figure 3B uses a normal scale for both axes. To produce a linear model, the Species Area Relationship equation is usually shown as a log relationship:

$$\log S = \log C + z \log A$$

The general equation for a linear relationship is usually written as:

$$Y = mx + b$$

The slope of the line is m and b is the Y-intercept. The Species Area Relationship means the same thing, and can be arranged as:

$$\log S = z (\log A) + \log C$$

**Continued**

**Model Skill: Variables and Constants in the Species Area Equation, cont.**

Whether something is an island for a particular species is also a matter of scale. For a fish, the pond might be an island. For an aquatic insect in the same pond, each patch of algae might be an island on a rocky substrate.

**Check Your Understanding**

- What is a habitat island?
- Why would larger islands support more species?

### Proximity to Mainland Increases Island Biodiversity

Generally, islands that are close to a large landmass have more species than similar-sized islands that are more isolated. It is easier for colonizers to reach near islands and establish populations or to reestablish populations that have gone extinct. The colonizers of the island usually come from nearby mainlands or islands, but some may come from far away. Birds and bats can fly long distances and may carry seeds with them. Ocean currents can carry floating material long distances as well. Additional colonizers from the mainland can also increase the genetic diversity of established populations.

Researchers tested whether ant species diversity were a function of island size and distance on islands in the Boston Harbor Islands National Recreation Area in Massachusetts. They used data from a 5-year long collection of arthropod biodiversity information. Because they were using a long-term data set, they discovered a lot of variation in which species were found in each survey. Had they only used one survey, they would have missed many species that were present on the island but not using a particular location at a particular time. Their findings were similar to what the island biogeography models would predict, but did not follow exactly the same pattern (Figure 5).

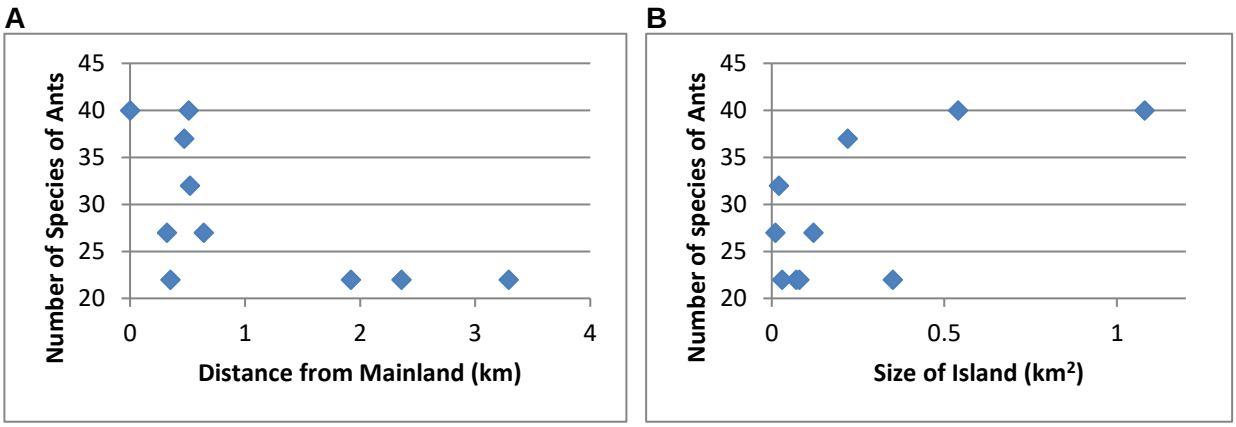



Figure 5. Number of ant species living on islands in Boston Harbor, MA, USA as a function of distance from the mainland (**A**) and size of island (**B**). Drawn from data in: Clark, A.T., Rykken, J.J., Farrell, B.D. (2011). The effects of biogeography on ant diversity and activity on the Boston Harbor Islands, Massachusetts, U.S.A. PLoS ONE 6(11): e28045. doi:10.1371/journal.pone.0028045

**Analyze the Figure**

- What influence did distance from mainland have on the number of ant species?
- Was the relationship linear, or did it follow another pattern? Explain your answer.
- What influence did size of the island have on the number of ant species?
- Select an outlier and propose at least one reason that it may have had fewer species than islands that size or smaller.

The same relationship applies to habitat islands. If a particular habitat patch is close to a source of species, it would be expected to have more species than an area that is further away, assuming that all other factors are equal. Again, scale and characteristics of the species of interest are major considerations. A difference of 10 km may make no difference to bird diversity, while the same distance might be a major factor in patch distance for the biodiversity of reptiles.

**Check Your Understanding**

- Why would more isolated islands support fewer species?
- Can both size and proximity to the mainland influence species diversity on a habitat island?

**Island Biogeography Concepts are Critical in Species Conservation**

Construction of roads, buildings, or farms can divide large areas of habitat into several smaller habitat islands. This is called **habitat fragmentation**. Conservation reserves (habitat patches that are protected) are types of habitat islands. Many of the concepts learned from studying actual islands apply to preserving species in both terrestrial and aquatic habitat islands. For example, larger areas are likely to allow for conserving more species because they provide more resources and more variation in resources. Connections between patches are important so that habitat islands can provide for colonists for each other. **Corridors** of suitable habitat between the patches increase connections. So does having patches closer together.

There are some trade-offs in these decisions. Having few large patches of habitat is usually better for large carnivores than many small patches, even if the total conserved area is similar. It takes a lot of land to produce enough food for large carnivores, so a viable population may need to be very large. Edges of conserved areas can increase the risk of disturbance from humans and other species on unprotected areas. Young individuals, including seeds, are probably more likely leave the reserve if there are more edges. On the other hand, if there are only one or two large reserves, a disaster or disease might wipe out species on the entire reserve. Multiple smaller reserves spread the risk. Genetic exchange between patches can increase genetic diversity (see **Evolutionary Perspective: Habitat fragmentation, metapopulations, and genetic diversity**). The effective size of reserves will depend on the scale and mobility of the species involved. A patch that supports a viable toad population may not be useful in the conservation of wolves. For more on fragmentation and extinction, see **Hypothesis Testing: Can Species-Area Models Predict Wildlife Extinction on Reserves?**

When an island is first formed, it may not be a suitable habitat for many species. A volcanic island in the ocean starts off as barren rock. As time goes on, islands can be colonized by various species, some of which create a suitable habitat for other species (recall facilitation from Chapter 16). Species that travel well and are common on the mainland will be more likely to colonize an island. The first individual to arrive on the island will be a new species in the island's community. After that, any individual may be a new species or just an addition to the population of its species.

Early on, the chance that an individual is the first to colonize the island is high. Few species are there. As the island accumulates new species through immigration, the probability of new arrivals being species that have not already colonized the island decreases (Figure 6). As an analogy, imagine that a business you visit often is giving out game cards as a promotion. The more cards you collect, the less likely it is that the next card will be one you do not already have.

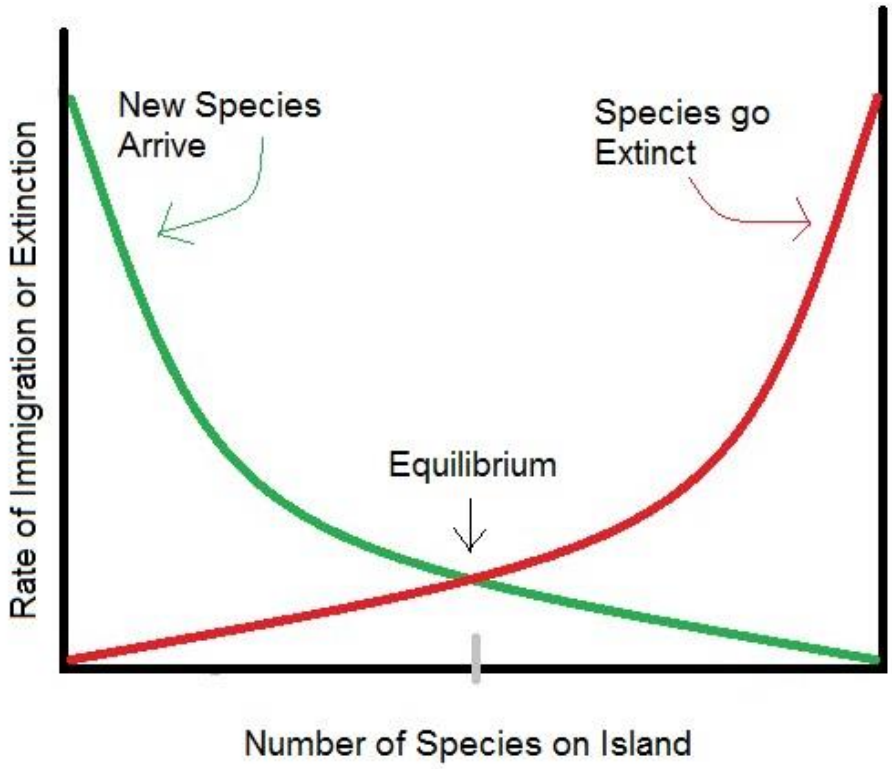



Figure 6. A model of island biogeography. The green line shows that as the number of species on an island increases, immigration of new species decreases. The red line shows that as the number of species present on an island increases, the rate of extinction increases. The lines cross at the equilibrium point. There are no units on the graph because characteristics of the specific island will determine the equilibrium point. Based on: McArthur, R.H., & Wilson, E.O. (1967). The theory of island biogeography.*Monographs in Population Biology*, *1*, 22.

**Analyze the Figure**

- According to this model, what happens to the extinction rate as more species arrive on the island?
- Explain why the immigration rate and extinction rate have opposite patterns.

The more species there are on an island, the more likely it is that species will go extinct from the island. Having more species means more species that can go extinct. It also means increased competition. At some value of species richness, the rate of new species colonizing the island will be the same as the rate of resident species going extinct. This is the **equilibrium** point because when the system is disturbed, it will tend to return to the same point. Imagine that a drought wipes out several species on the island. What will happen to the immigration rate? How will that influence the richness of species on the island? Equilibrium models assume a certain amount of stability. For example, a major disaster might destroy habitat. This would cause high levels of extinction and prevent colonization, meaning that the system would not return to equilibrium. To learn more about this model, see **Taking It Further: Multiple Equilibrium Points**.

**Taking It Further: Multiple Equilibrium Points**

The typical species richness of the island will be determined by factors such as productivity, size, and distance to mainland. The influence of these last two factors is used in a slightly more complex version of the island biogeography model (Figure 7). An island closer to the mainland will get more new species than one that is far away, particularly early in colonization. (The difference decreases because all possible colonists could potentially arrive eventually.) A larger island will have a lower extinction rate because there are more resources and variation in habitat. This means that islands will have different equilibrium points based on their size and distance from the mainland. Although it is not the case in the model, the size of an island might influence extinction more than its isolation, while the distance to the mainland may have a greater influence on immigration.

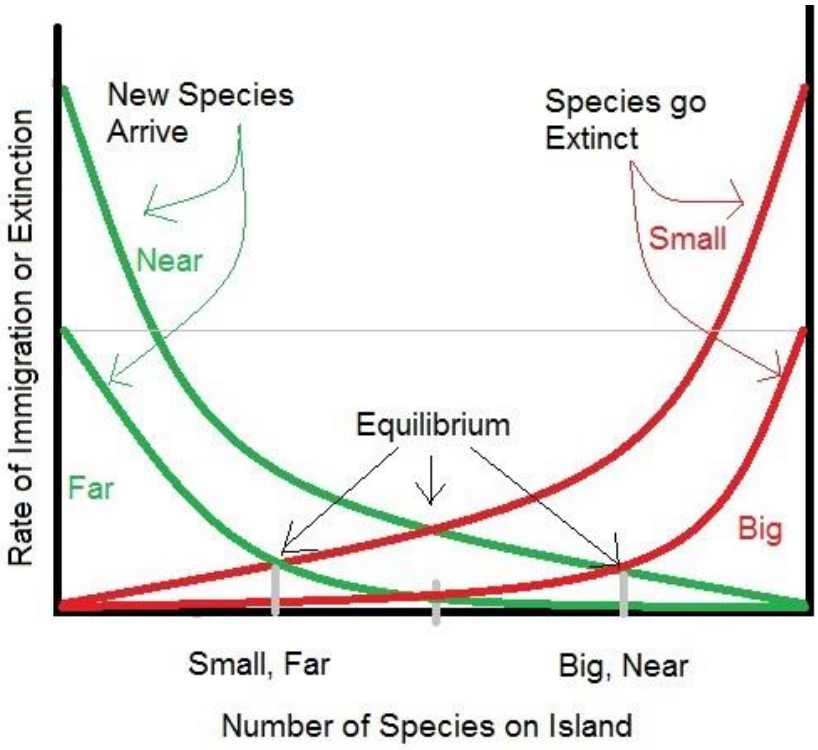



Figure 7. Model of island biogeography showing different possible equilibrium points. Small islands far from the mainland will have much lower species richness than large islands that are close to the mainland. After McArthur, R H., & Wilson, E.O. (1967). The theory of island biogeography. *Monographs in Population Biology*, *1*, 22.

**Analyze the Figure**

- According to this model, which type of island will have the fewest species at equilibrium?
- Imagine that a major storm caused extinction of several species on a big, near island. What would happen to the immigration rate?

**Evolutionary Perspective: Habitat Fragmentation, Metapopulations, and Genetic Diversity**

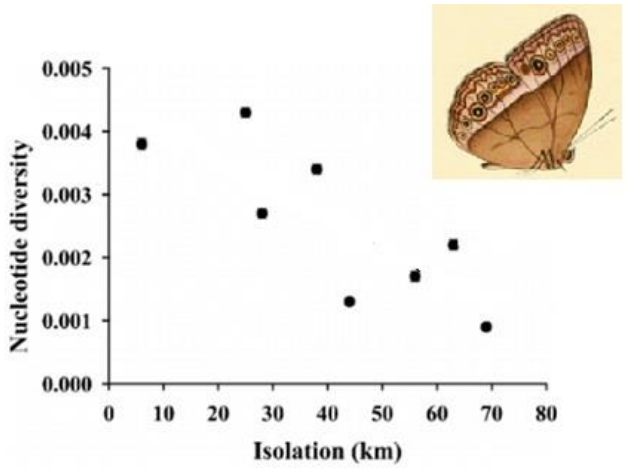



Figure 8. Effect of patch isolation (distance from another habitat patch) on mitochondrial genetic diversity of butterflies (*Mycalesis orseis*) in a Bornean tropical rainforest that has been fragmented by logging. $R^2 = 0.65$. Benedick, S., White, T. A., Searle, J. B., Hamer, K. C., Mustaffa, N., Khen, C. V., Mohamed, M. ,schilthuizen, M. & Hill, J. K. (2007). Impacts of habitat fragmentation on genetic diversity in a tropical forest butterfly on Borneo. *Journal of Tropical Ecology*,*23*(06), 623-634.
Image: https://upload.wikimedia.org/wikipedia/commons/1/16/Mycalesis_orseis.JPG

Genetic diversity can protect a population from being wiped out by a new threat. For example, genetic differences lead to differences in immune systems between individuals. In a population with high diversity, some individuals may be able to fight off disease A, but be unable to fight off disease B, while other individuals can fight off disease B, but not C. If disease B sweeps through a population, some individuals will probably survive and repopulate the area. If a population has low genetic diversity, all individuals will have similar immune systems. One disease might kill every individual. Other changes in either the environment or in other species (such as parasites or competitors) could also wipe out a population if all individuals are genetically similar.

Habitat patches can have low diversity if they were founded by a small number of individuals. For example, a large forest in Borneo was divided into many small fragments due to logging. This divided the habitat of a particular butterfly species into patches. The individuals in each patch may only have a portion of the diversity that was in the entire butterfly population before the forest was fragmented. If individuals can move between patches, they can increase genetic diversity because the genetic patterns that are common in one patch may be rare in another. One study showed that butterflies in isolated forest patches had lower mitochondrial genetic diversity than butterflies in patches that were close to other patches (Figure 8).

**Continued**

**Evolutionary Perspective: Habitat Fragmentation and Genetic Diversity, cont.**

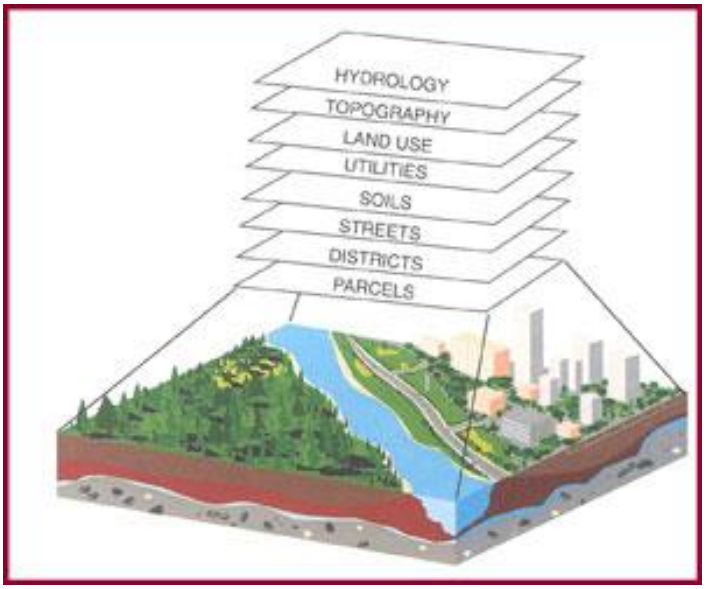
A collection of populations that have an effective rate of genetic exchange is called a **meta-population**. Some meta-populations will have a more gene flow than others. The limitations can be the ability of individuals to move or the risks and costs of moving between patches. The less movement between the patches, the more inbreeding there is in each patch.

Zoos create artificial meta-populations by creating gene flows between different zoos around the world. This used to require shipping animals. Now frozen sperm and embryos can be exchanged. These practices can increase genetic diversity and may increase long term viability of populations and species.

Small populations will not only start with lower genetic diversity (due to a low number of founders), they can also lose diversity more easily than large populations can. Imagine a rare allele that only 1% of the butterflies has. If a habitat island has 100 individual butterflies, only one individual will have that rare allele. If a something kills that one individual, the gene disappears from the population. The event may be entirely random, having nothing to do with the particular allele. If there were 1,000 individuals, ten would have the rare allele. If random events killed ten individuals in the population, it is unlikely that all of the individuals with the rare allele would be killed. In short, large populations are less likely than small populations to randomly lose rare alleles.

## Global Information System Technology Can Illustrate Complex Landscape Patterns

Global Information System (GIS) technology is important for analyzing patterns in space and time. Powerful computers have made landscape ecology much more sophisticated, but the idea of overlaying several types of information on the landscape is older than the computer (see **Make the Medical Connection: Landscape Patterns and Epidemiology**). GIS data can come from a variety of sources, all of which can link information to specific locations. For a long time, different types of information would be plotted on transparent sheets that could be literally laid over a map in different combinations. Now these **overlays** are data sets that include information on specific locations (Figure 12).



http://www.environment.fhwa.dot.gov/integ/resources.asp

Figure 12. Visual model of some common types of overlays in a GIS system.

**Analyze the Figure**

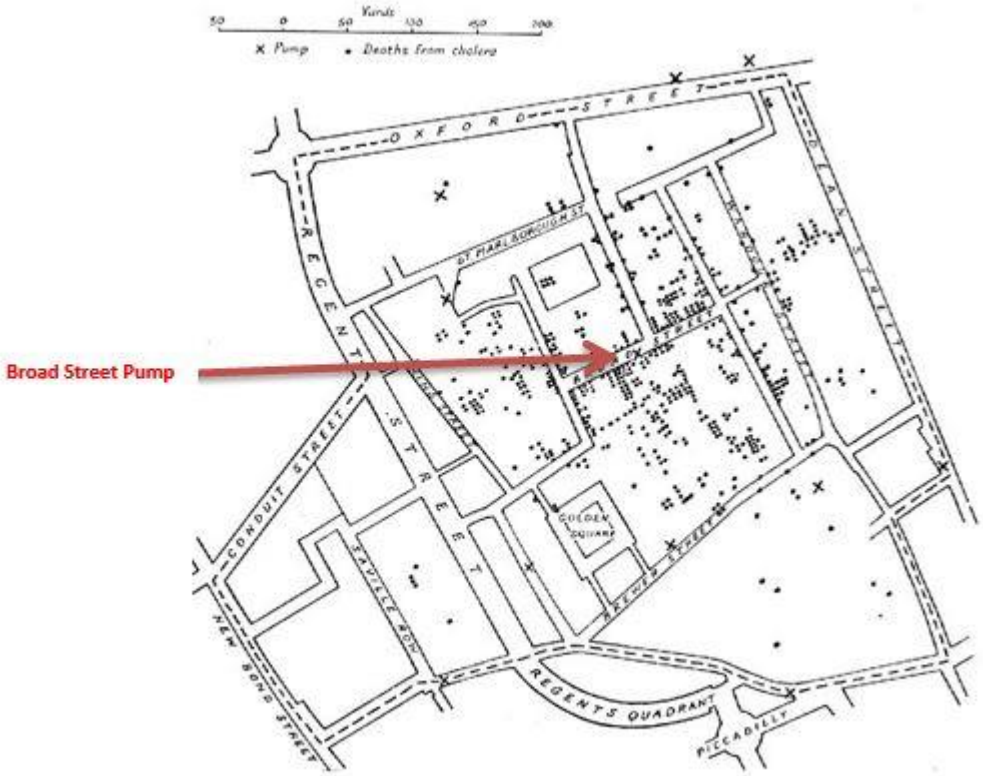
- Which of the variables in one overlay is likely to influence the values in another overlay? Explain your reasoning.
- Which of the patterns in the overlays is easiest for community planners to alter?

Ecologists can use the spatial information in GIS to identify patches with complex combinations of characteristics. For example, understanding vegetation patterns might involve looking at the landscape of soil types, moisture levels, wind patterns (which could influence pollen or seed dispersal), and overlap in the range of different species. Managing species requires understanding current and planned land use as well as natural communities. For an example of how overlays are used in land use decisions, see **Why It Matters: Urban Planning and Landscape Information**. You can explore your own neighborhood using publicly available GIS information, see **Do Try this at Home: GIS and Your Community**.

**Make the Medical Connection: Landscape Patterns and Epidemiology**

Public health agencies use landscape patterns for detecting emerging diseases. In 1854 in London, hundreds of people were dying of cholera, which causes severe diarrhea and vomiting. No one knew what caused the disease, but physician John Snow hypothesized that water from a contaminated well was the source.

People got their water from public pumps. Sewage was stored in pits under houses, which might overflow before the waste could be pumped into the Thames River (the source of drinking water). Snow mapped the location of each public pump in that area of London (Figure 13). He then plotted the homes of over 500 people who had died of cholera. The first pattern showed that most victims had lived closest to the Broad Street Pump, but many victims lived nearer to another pump. Snow considered whether people might be using a pump that was farther "as the crow flies," but closer when he measured the route people would walk. A pattern emerged; the shortest route for most of the cholera victims was to the Broad Street Pump. Almost all the other victims had used the Broad Street Pump for various reasons. The pump was temporarily disabled, but construction of an actual sewer system came only after the "Great Stink" of 1858.

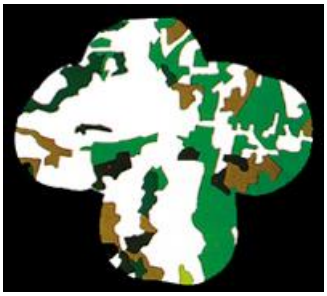



http://commons.wikimedia.org/wiki/File:Snow-cholera-map.jpg

Figure 13. Snow's original map of pumps (X) and the homes of people who died of cholera (dots). (Red arrow and label added.)

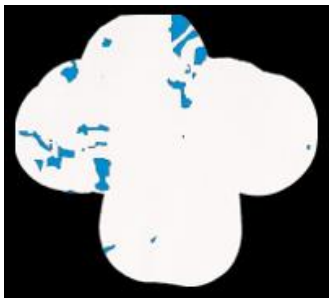
**Why It Matters: Urban Planning and Landscape Information**

A. Area served by the water company (blue) and adjacent area (white) that could be used.

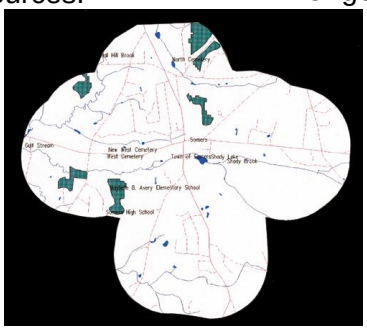


B. White spaces indicate land developed for homes and businesses.

C. White spaces indicate possible contamination sources.



D. Blue indicates geological conditions for good underground water supply.



E. Final map showing appropriate sites for a well (grayish green).
http://egsc.usgs.gov/isb//pubs/gis_poster/

Figure 14. Series of overlays used to site a well in Connecticut, USA. By excluding some areas and including others, optimal sites are identified.

Many urban planning decisions are made using GIS analysis of the landscape. Imagine that you were deciding where to drill a new well for your town's water supply. You can't put the well in a parking lot or someone's backyard. You would need to avoid any contaminated areas. The site would have to be a viable source of water. This combination of information would be very difficult to consider as lines of data, but when the data are viewed as overlays on a map, a clear set of options emerges (Figure 14).

- Who should decide what data are used in siting wells, landfills, and other projects?

**Do Try this at Home: GIS and Your Community**

Use a program such as Google Earth (free download at earth.google.com/) to see your home town or favorite location. Search for the location, then turn on different overlays to see various features of the landscape. (In Google Earth, customize the layers) What patterns can you see in the landscape? Try zooming in and out to see which patterns appear and disappear.

If you search online by “GIS” and your city’s name, you may find interactive maps that show many types of data from flood plains and fault lines to property values and foreclosures.

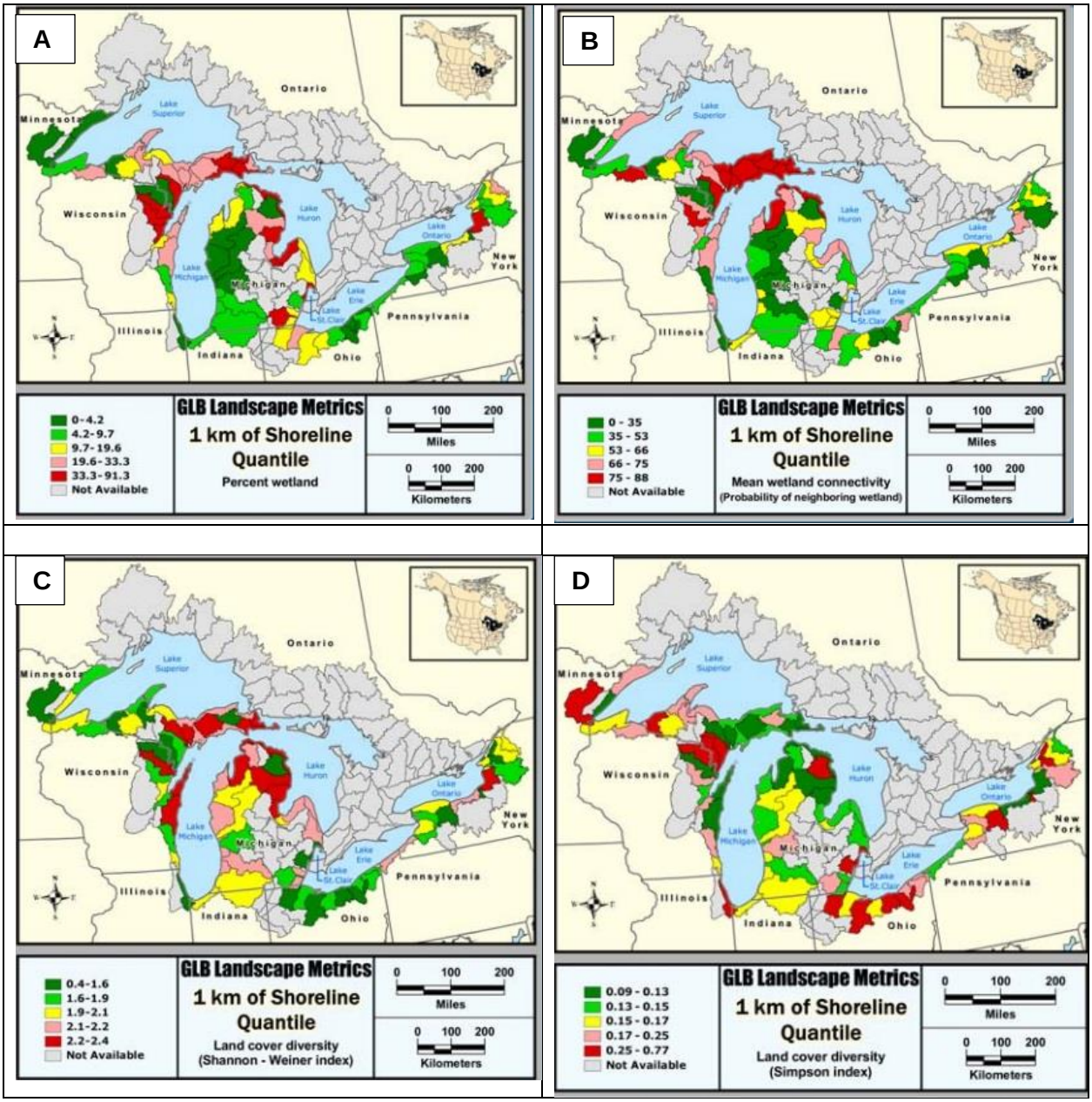
Imagine that you wanted to identify they highest quality habitat in a landscape. The most reliable way would involve directly measuring many factors, but this is usually too expensive and time consuming, especially when the area is large or inaccessible. Using **indicators** can give a reasonable basis for management decisions. These meta-variables are usually fairly easy to measure, but capture more complex and interesting information about multiple variables in an area.

As an example, suppose that a city wanted to identify the best areas of a city so that they could improve additional areas of the city. The variable "best" seems rather subjective and difficult to measure. However, one variable—home price per square foot of home size—would be a good indicator of desirability of an area. The value of that indicator would be a function of many other variables, including quality of schools, feeling of community, and aesthetics of the neighborhood. Some of these variables might be difficult to measure, but cost per square foot is readily available data, and gives a reasonable indicator of quality of life in a neighborhood.

In landscape ecology, "quality" is also a meta-variable that might be influenced by many biotic and abiotic variables. The presence of native species with particular habitat needs is often used as an indicator of habitat quality. Reproductive rate of particular species can indicate habitat quality. Patterns such as habitat size, connectivity, and diversity would be potential indicators of habitat quality. Measurements that can be taken by computerized analysis of satellite pictures are often used as indicators because it is relatively inexpensive to gather these data over a large area.

The Great Lakes contain about 20% of Earth’s fresh surface water. Resource managers studying the Great Lakes Basin are faced with a complex landscape that crosses state, provincial, and national borders. Each lake has unique characteristics, but all are connected. The lakes are bordered by cities, beaches, and coastal wetlands, such as swamps or marshes. Coastal wetlands are of particular interest because they provide many ecosystem services. They are habitat for many terrestrial and aquatic species. Wetlands decrease flood risk and increase lake productivity. The Great Lakes are a critical source of water and waste disposal. Wetlands help to remove wastes from water, improving water quality. Unfortunately, wetlands are threatened by development, toxins, and decreased water flow due to human activity.

When the US Environmental Protection Agency (EPA) wanted to evaluate habitat quality in the Great Lakes, the agency identified many potential indicators, some of which are shown in Figure 15. They divided the area into patches by ecoregion (e.g. boreal forest, north central hardwood forest, or wetland). They then analyzed images for indicators of habitat quality. For example, the percent wetland in a patch could indicate larger habitat islands. It could also mean many small habitat islands. Knowing which areas have a high probability of being connected to another patch of wetland (wetland connectivity) would indicate whether species could move between patches. Habitat heterogeneity can be measured using a slight modification of the Shannon-Weiner Diversity Index used in Chapter 17. Instead of species, habitat types are used. Area is used in place of number of individuals. This index has flaws because including habitat types such as urban or industrial areas would give a higher score, even though suitable habitat would be lower. The Simpson Land Cover Index (D) is similar to the Shannon-Weiner Index, but is not influenced as much by rare habitats, such as a small development. Taken together, these indicators provide a useful estimate of habitat quality. Managers have to use professional judgment to weigh the value of each indicator along with several other issues, such as stakeholder interests.




http://www.epa.gov/nerlesd1/land-sci/pdf/EPA_600_X-06_002.pdf

Figure 15. Indicators of coastal wetland quality in the US region of the Great Lakes Basin. Patches have different ecoregions (smaller scale biomes). **A** Percentage of wetland. Red has the most. **B** Connectivity: probability that the area near the plot will also be wetland. Red is the most connected. **C** Shannon-Weiner index of diversity of habitats. Red is the most diverse. **D** shows the Simpson land cover index of habitats within the plots. Red is the most diverse.

**Analyze the Figure**

- Identify two or three areas that have a high Shannon-Weiner Index of diversity.
- Identify an area that has high levels of both wetland and wetland connectivity.
- If you were preserving an area, where would you put it, based on the indicators in the figure? Explain your choice.

**Hypothesis Testing: Can Species-Area Models Predict Wildlife Extinction on Reserves?**

Wildlife reserves are habitat islands. Ecologists might ask whether the same models that predict species richness on islands could be used to predict the rate of local extinction of wildlife in reserves. The three main hypotheses possible from this question are:

Hypothesis 1: Species loss in reserves can be explained by Species-Area models alone.

Hypothesis 2: Species loss in reserves can be partially explained by Species-Area models, but other variables are important.

Hypothesis 3: Species-Area models are not useful in explaining species loss in reserves.

Brashares et al. (2001) investigated this question using six wildlife reserves in the West African country of Ghana. The reserves had been established 21-23 years before the study. The researchers plotted the expected extinction rate (loss of large mammalian species) predicted from the species-area models as the predicted extinction rate, then plotted the actual (observed) extinction rate (Figure 16).

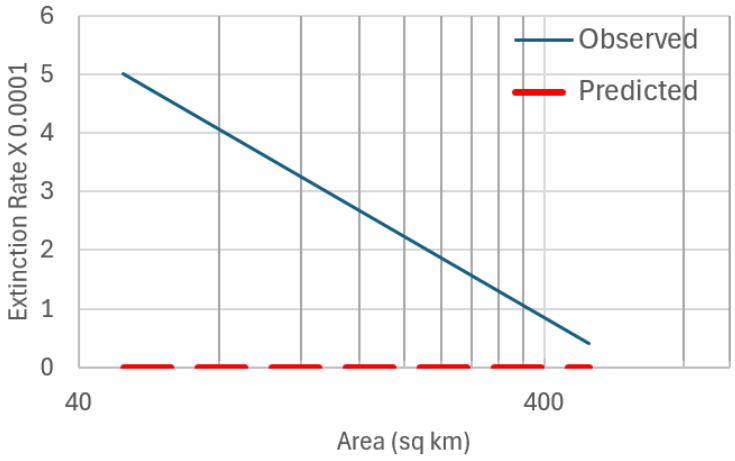



Figure 16. Correlation between rate of extinction of large mammals and reserve area based on data from 6 African reserves. The "predicted" line is the extinction rate based on size of reserve alone (species-area model). Modified from: Brashares, J. S., Arcese, P., & Sam, M. K. (2001). Human demography and reserve size predict wildlife extinction in West Africa. *Proceedings of the Royal Society of London B: Biological Sciences*, *268*(1484), 2473-2478.

**Analyze the Figure**

- According to the species-area model, how many species should have been lost from any of the reserves?
- Did reserve area influence extinction rate? Give evidence to support your answer.
- Which hypotheses are supported or refuted by these data?

The actual extinction rates were 28 times larger, on average, than the species-area model predicted. Loss rates were greatest for carnivores and lowest for ungulates (hooved animals). Researchers speculated that humans were hunting in the "protected" areas. Poaching can be difficult to measure directly, so researchers used the size of the human population near the reserves to examine whether human activity might explain species loss (Figure 17).

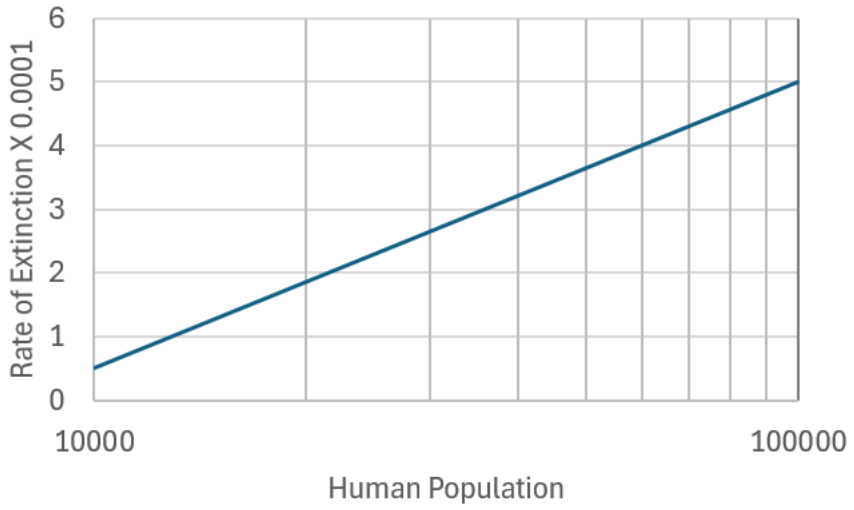



Figure 17. Rate of extinction based on the human population within 50 km of each reserve, $r^2$ = 0.87, p= 0.008). Modified from: Brashares, J. S., Arcese, P., & Sam, M. K. (2001). Human demography and reserve size predict wildlife extinction in West Africa. *Proceedings of the Royal Society of London B: Biological Sciences*, *268*(1484), 2473-2478.

**Analyze the Figure**

- What is the main pattern in the graph?
- Which hypotheses are supported or refuted by these data?
- Do you have a new or modified hypothesis to explain the pattern?

Researchers speculated that the hunting pressure might be greatest near the edge of reserves, so they selected one of the reserves and counted the large mammal species at different distances from the border of the reserve (Figure 18).

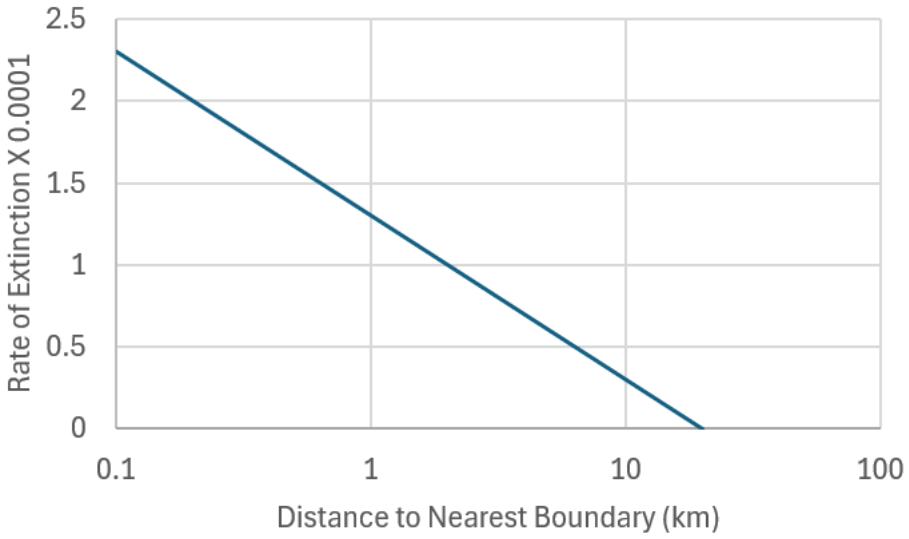



Figure 18. Extinction rates of large mammals for individual transects within a National Park in Ghana as a function of distance from the nearest park boundary. Modified from: Brashares, J. S., Arcese, P., & Sam, M. K. (2001). Human demography and reserve size predict wildlife extinction in West Africa. *Proceedings of the Royal Society of London B: Biological Sciences*, *268*(1484), 2473-2478.

**Analyze the Figure**

- What is the main pattern in the graph?
- Which hypotheses are supported or refuted by these data?

**Learning from the Case Study**

- What did the study tell us about extinction in the African reserves (what factors were important)?
- Why might edges be dangerous?
- If you were in charge of establishing and managing reserves like this, what actions might you take to reduce losses of large mammalian species?

**Case Study Part 2: Which Areas Should be Protected?**

In creating a Marine Protected Area (MPA) network, planners had to identify areas that would protect the maximum number of species of interest while causing the least disruption to human uses. People use the California Coast for many uses. Some of these are non-consumptive, meaning that they do not remove anything from area. Examples would be boating, swimming, and diving. Some consumptive uses are recreational, for example, people might fish from boats or docks. Some consumptive uses are commercial, for example, drilling for oil and gas or harvesting fish for sale. Planners were able to use overlays of where these uses occurred, and with what frequency to better understand how MPAs would influence stakeholders (Figure 19).

http://marineprotectedareas.noaa.gov/dataanalysis/atlas_ca/

Figure 19. A sample of the many types of usage data overlays used in siting California's Marine Protected Areas (MPAs). Interactive maps are available at http://marineprotectedareas.noaa.gov/dataanalysis/atlas_ca/viewer/.

The planners also had to understand biological systems to protect sites with the most potential for improving and sustaining populations of important marine organisms. Part of this task involved identifying quality habitat. A high-quality habitat for one species of interest might be a low-quality habitat for another, so planners had to map habitat types and species distribution, prioritize species and provide some mix of habitats.

Recall from Chapter 13 that conserving species requires understanding the threats to organisms at different ages. When designing the network of MPA's planners paid close attention to habitats where reproduction occurs. They hoped that these areas would be source areas, producing surplus organisms that could be harvested in unprotected "sink" areas without endangering the future of the population (see Chapter 10).

Some management concerns (such as strategies for decreasing runoff, managing fisheries, and monitoring precipitation) could only be addressed at the landscape or ecosystem level. The total area of the MPAs was important, but so was connectivity between the MPAs. If the areas were too far apart, there would not be enough movement of juveniles to the unprotected areas. This would mean reduced harvest. If the areas were too close together, too many protected areas would be needed, angering stakeholders and perhaps delaying or preventing the MPA plan. A local problem could also wipe out several patches if they were too close together. To complicate matters, planners couldn't just decide on one optimal distance. Juvenile marine organisms are usually dependent on water currents for most of their movement. They may be able to control small scale movements but are too small to fight currents or move long distances on their own. Careful study of currents on both small and large scales were essential for predicting where larvae produced in one area would eventually go.

**Learning from the Case Study**

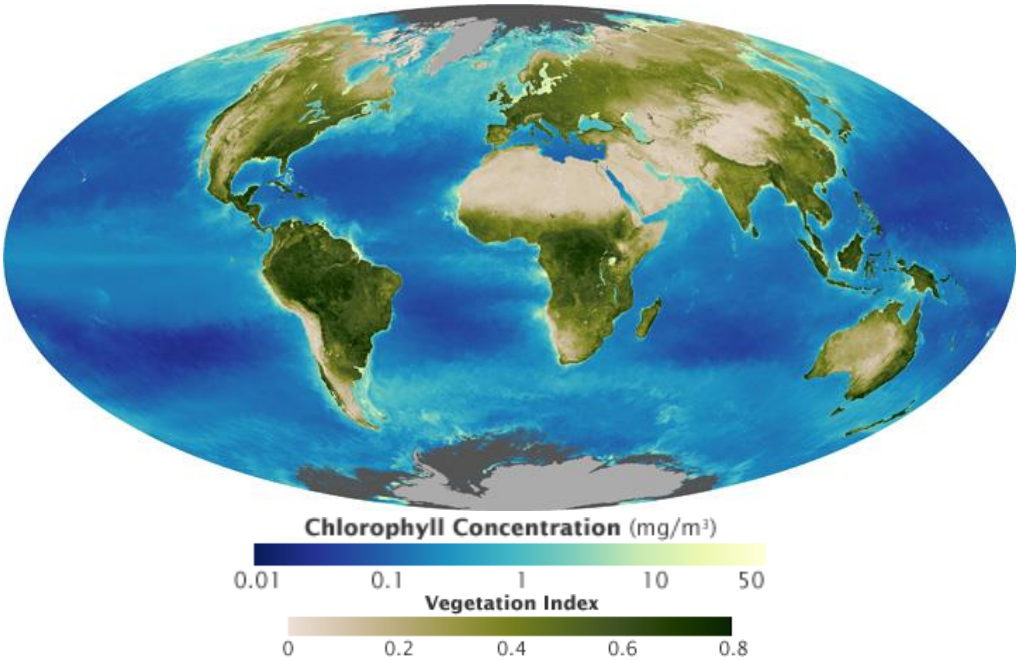
- What factors did the conservation managers have to consider in designing the network of reserves?
- Describe an example of how the different goals of the plan might have conflicted.

**Check Your Understanding**

- What is an overlay? Give an example.
- How can GIS mapping improve understanding and management of landscapes?
- What are habitat quality indicators, and how can they be used in management decisions?

**The Biosphere Connects All Life**

The largest ecological scale is Earth itself, with all of its ecosystems, including the living inhabitants and abiotic resources, such as the atmosphere, water, and soil. The source of Earth's constant energy input is the sun, so Earth is not a closed system. As discussed in Chapters 6 and 8, solar input varies across the globe, resulting in global weather and climate patterns. These patterns drive global productivity (Figure 20). The weather and climate in one area—and the resulting productivity—cannot be separated from global movements of wind and water currents. Changes in the trade winds near the equator can lead to starving marine mammals on the California Coast and drought in Illinois.



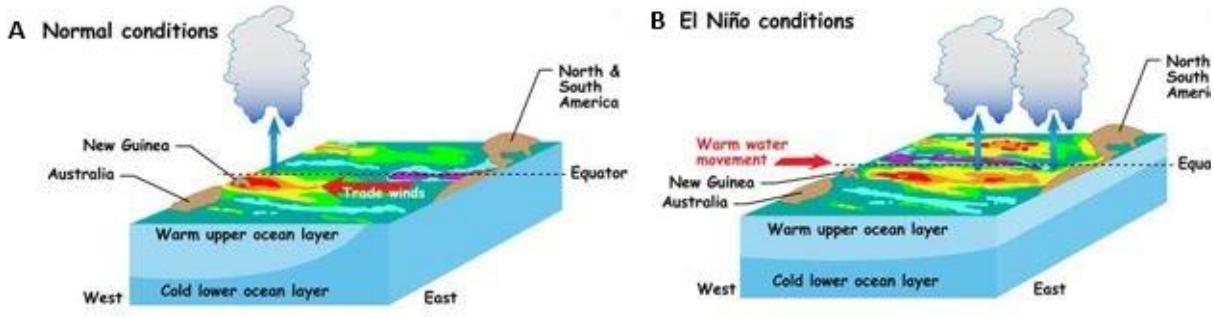

http://earthobservatory.nasa.gov/Features/WorldOfChange/biosphere.php

Figure 20. Productivity in the biosphere, shown as concentration of chlorophyll—a pigment used in photosynthesis—in water and as vegetation index on land.

**Analyze the Figure**

- Where are concentrations of chlorophyll and vegetation high and low?
- What happens to productivity levels in water near continents?
- Do opposite sides of the same continent have the same vegetation levels? Explain this pattern.

Recall from Chapter 6 that heating of oceans near the equator causes a lot of evaporation. As this water vapor rises and cools, the water condenses, causing rainy climates near the equator. Winds near the equator usually blow the warm surface water and heavy equatorial rains toward Australia and Indonesia (Figure 21 A).




http://climatekids.nasa.gov/el-nino/

Figure 21. Major differences in water currents, precipitation, and thermocline during normal (A) and El Niño (B) years. Colors indicate water temperature, with red being warmest and blue being coldest.

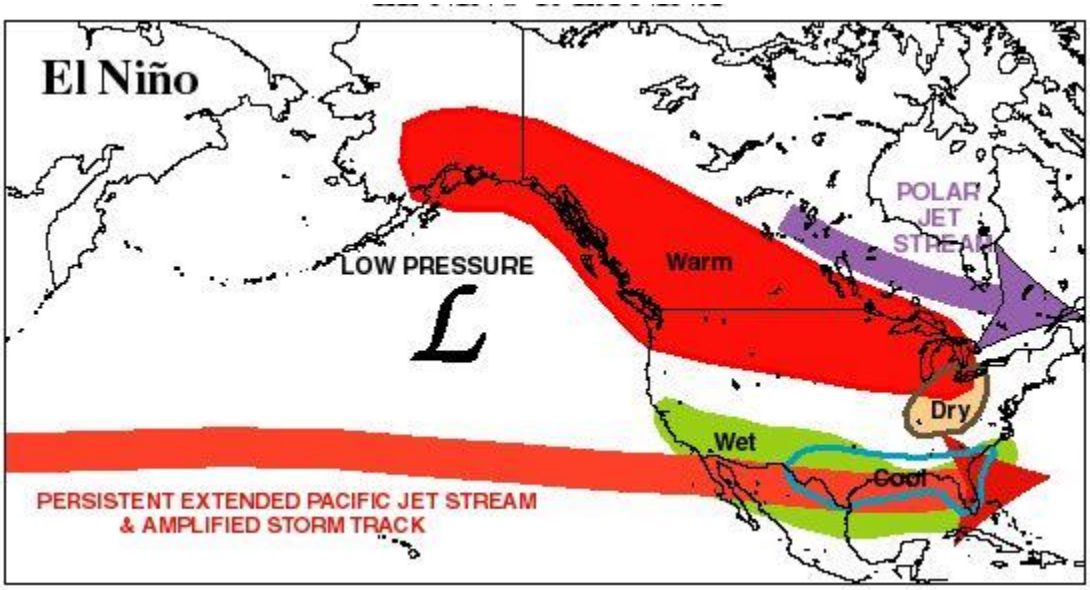
**Analyze the Figure**

- Which conditions—Normal or El Niño—are influenced by trade winds moving west from the Americas?
- Which conditions—Normal or El Niño—lead to warm water along the west coast of the Americas?
- Why do El Niño conditions lead to heavy precipitation on the California Coast?

Recall from Chapter 9 that warm water is less dense than cold water, so thermoclines can form, with warm water floating on cold water. When warm water is pushed west by winds, it displaces deeper, cooler water back toward the Americas. Recall from Chapter 9 that when cold deep water is forced up the continental shelf, it brings nutrients into the photic zone, creating high productivity.

During El Niño years, water temperatures in the eastern Pacific Ocean near the Equator are warmer than usual (Figure 21 B). Winds that normally blow west are weak or even blow east, leaving warm surface water near the Americas. This causes heavier rain near the Equator in the Americas and droughts in Indonesia and Australia. Without the upwelling of nutrients, food webs

on the west coast of the Americas can collapse. These weather systems also influence weather patterns worldwide, making some areas drier than normal and other areas wetter (Figure 22).




http://www.srh.noaa.gov/tbw/?n=tampabayelninopage

Figure 22. Influence of El Niño and associated phenomena on US weather patterns. The low pressure zone is due to warm air masses, which are less dense than cold air masses. Jet streams are strong wind patterns.

**Analyze the Figure**

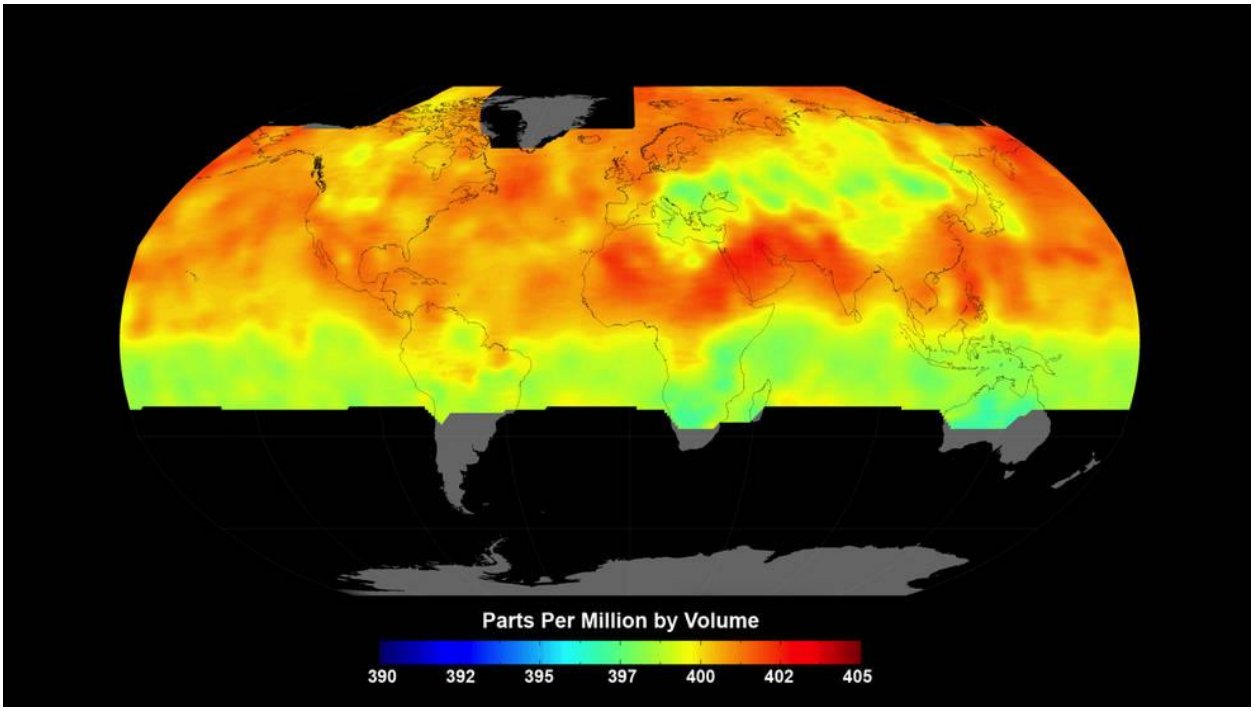
- Which regions of the US will be warmer than usual during an El Niño year?
- Which regions of the US will be drier than usual during an El Niño year?

These temperature changes are cyclic, coming every 5-7 years and they vary in intensity. The US National Oceanic and Atmospheric Administration (NOAA) monitors wind, ocean temperatures, and ocean currents worldwide using buoys equipped with sensors. The difference between water temperatures in the eastern and western Pacific is a major indicator of conditions. Knowing the pattern of ocean temperatures and currents helps in predicting which regions have an increased risk of flooding or drought (which increases fire risk). Using a global-scale view of Earth's oceans allows a much better understanding of local weather patterns and allows longer-scale prediction of patterns.

**Misconception Alert: If we damage Earth's ecosystems, we can travel to other planets and colonize them.**

**FALSE.** Even if we discovered a habitable planet or moon, then overcame the many technological and biological issues involved in reaching it, the cost would be so high that it would not be feasible to relocate Earth's inhabitants.

Most of the maps we see show political borders, such as countries, states, or counties. But there are really no borders in the biosphere. Nutrients, pollutants, diseases, and invasive species travel the globe, sometimes in unpredictable ways. One example of this is the effect of greenhouse gases on the biosphere. As discussed in Chapter 5, carbon dioxide in the atmosphere can come from many sources, but the increasing levels since the industrial revolution have come mostly from the burning of fossil fuels such as oil, coal, and natural gas. Carbon dioxide does not stay where it is produced. Global wind patterns move gases throughout the biosphere (Figure 23). The temperature increases due to higher greenhouse gas levels influence global weather patterns.




http://www.nasa.gov/feature/jpl/excitement-grows-as-nasa-carbon-sleuth-begins-year-two

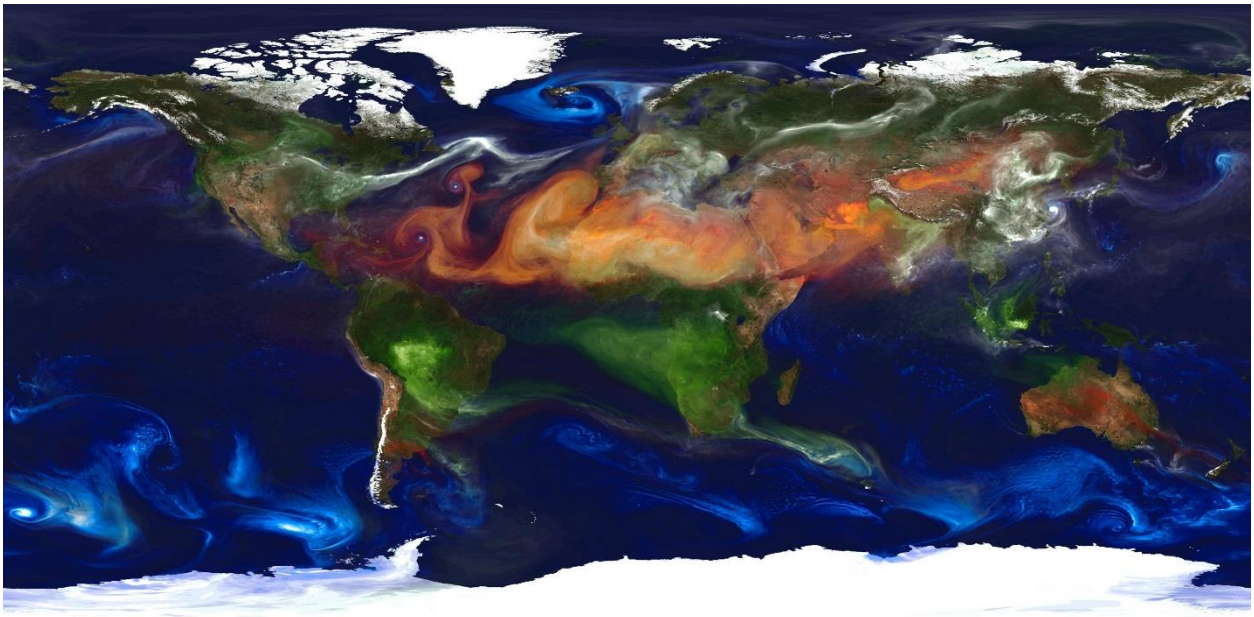
Figure 23. Global $CO_2$ levels as measured by satellite. Black and gray areas were not in the monitoring range of the satellite.

**Analyze the Figure**

- Where are $CO_2$ levels lowest?
- Identify an area where $CO_2$ levels are high, but fossil fuel burning would be low.
- How could the $CO_2$ be high in the middle of an ocean?

Aerosols are fine particles that can be carried in the atmosphere. They can come from natural sources (such as dust and sea salt) or from industrial activity. NASA used complex computer simulations of global wind patterns to predict how some aerosols might move throughout the biosphere (Figure 24). These aerosols decrease air quality and can influence global temperatures by reflecting light (if they are light colored) or absorbing light (if they are dark colored). Changes in local and global temperature lead

to changes in wind patterns. Aerosols also provide a place for water vapor to condense in the atmosphere, causing cloud formation.



https://www.nasa.gov/image-article/portrait-of-global-aerosols/

Figure 24. Image of aerosol movements in the global atmosphere as predicted by computer models. Red tones indicate dust. Blue tones indicate salt. Green tones indicate smoke from fires. White indicates sulfides from fossil fuels or volcanic activity. For an animation, see: https://svs.gsfc.nasa.gov/31171/.

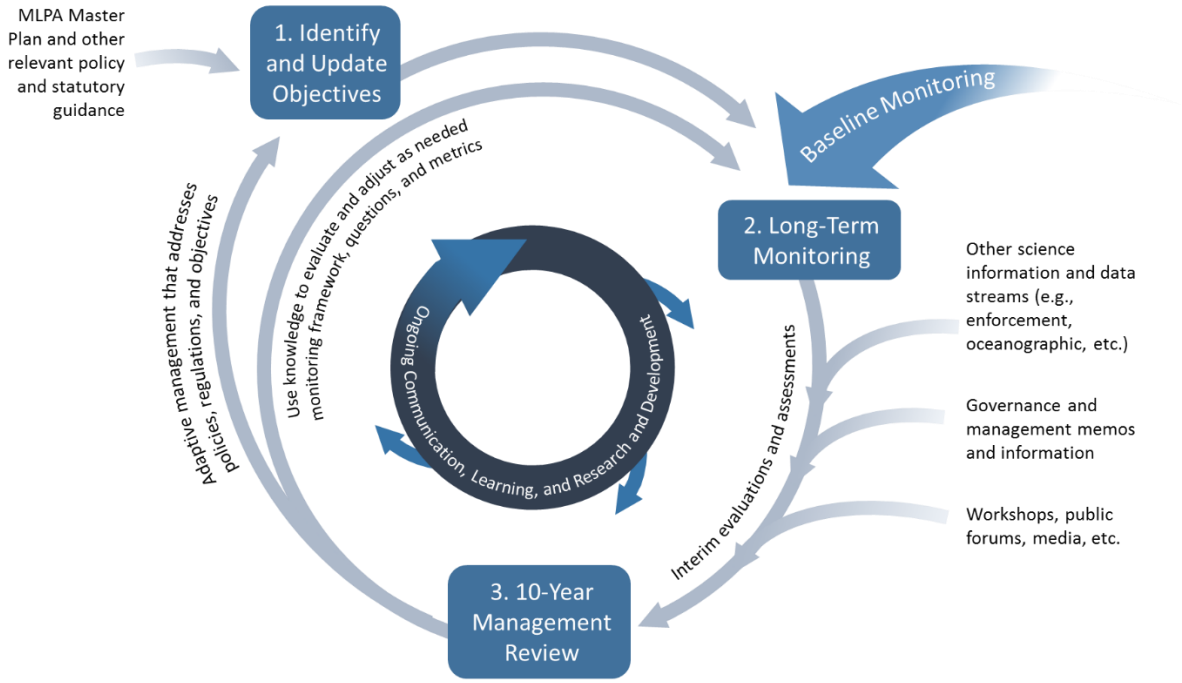
**Analyze the Figure**

- Could a dust storm in the Sahara Desert cause air quality issues in Florida? Describe your evidence.
- Would it be possible to predict exactly where the smoke from a particular forest fire might travel? Explain your reasoning.

As discussed in Chapter 10, humans can change species ranges intentionally or unintentionally. Some species will find a suitable habitat that is free of their predators, parasites, and major competitors. These species—including disease-causing organisms or vectors and pests—can become invasive. When ecologists or public health officials try to predict local threats, they must use a global perspective. Often, these officials know that a distant danger could cause a local crisis, but they have no way to prevent the movement of the threat. They can only prepare for it.

**Case Study Part 3: Planning for Climate Change**

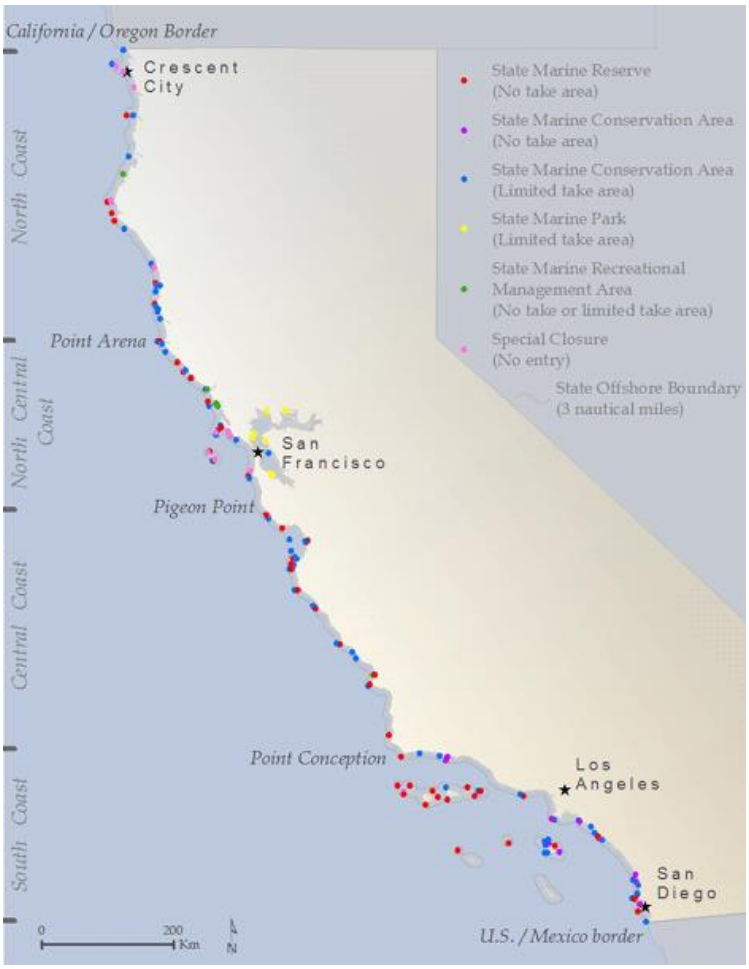
The MPA network in California is not isolated from global patterns. Climate models predict increases in temperature of the water on California's coast, influencing water flow patterns and habitat quality. An adaptive model is used to respond effectively to changes that can influence MPA effectiveness (Figure 25).




https://wildlife.ca.gov/portals/0/Images/marine/mpas/ManagementPage/MPA_management_process.png

Figure 25. MPA adaptive management process. This model was designed to preserve biodiversity despite potential changes in climate and other factors.

Eventually, the temporal and spatial information and models were used to develop a network of MPAs with different levels of protection (Figure 26). Reserve managers will be monitoring populations in the network and will probably be making changes due to both predictable and unpredictable changes in landscape patterns.




https://www.wildlife.ca.gov/Conservation/Marine/MPAs/Network

Figure 26. Map of California's Marine Protected areas. Different colored dots indicated different management designations and levels of protection.

**Learning from the Case Study**

- Why would global climate change influence plans along the California Coast?
- How were both spatial and temporal scales important to consider in designing the MPA plan?

**Check Your Understanding**

- Why must El Niño be understood at a global scale rather than as local weather patterns?
- What local activities can influence the entire biosphere?
- How might activities in another part of the world influence your community?

# Key Concepts

- Landscapes are areas containing patches that differ in important ways.
- Different species experience space and time at different scales.
- Different properties emerge at different levels of organization.
- Size and position of habitat islands influence biodiversity.
- GIS systems provide critical landscape information
- Global patterns can explain and predict local patterns.

# Apply the Concepts

**Learning Outcomes**

1. *Explain the importance of scales of time, space, and organization in the study of ecology*
2. *Apply landscape ecology concepts to issues of species conservation.*
3. *Accurately analyze processes behind global patterns such as weather, biodiversity, productivity, and movement.*

1. Refer to Figures 2 and 27.

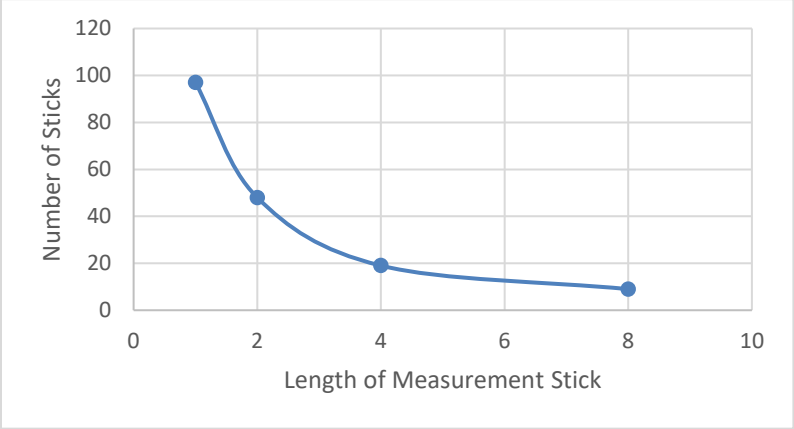



Figure 27. Estimates of the coast of Great Britain. *(Learning Outcome 1)*

A. What general principal does Figure 24 illustrate?
B. What is the ecological importance of this principal?

2. If you were trying to determine the cause of a local die-off in amphibians, what different levels of space and time would you study? Give specific examples, and state why that level is important. *(Learning Outcome 1)*

3. A. Examine the patterns in Figure 15. Identify an ecoregion patch that has a very high habitat quality. Circle this on your map. Explain why you selected this area, making connections between the indicators and habitat quality *(Learning Outcomes 2 and 3)*

   B. Explain how the factors you identified in 3A would help to promote biodiversity. *(Learning Outcomes 1 & 2)*

4. Recall the influence of disturbance on diversity (Chapter 17). Apply the concepts of island biogeography to explain why a landscape with frequent but small fires would have greater biodiversity than a landscape that had either no fires, or fires that burned the entire landscape. Assume that the small fires occur at different times. *(Learning Outcomes 2 & 3)*

5. Why would a lake with a lot of habitat heterogeneity potentially be more productive than a more homogeneous lake? (*Learning Outcomes 1 and 3*)

**Unit VI: The Larger Picture**

# Chapter 19: Human Impacts and Interventions

## Case Study Part 1. Can Mountain Gorillas be Saved?

Burton, 2013

Figure 1. Wild mountain gorillas (*Gorilla gorilla*) in Volcanoes National Park in Rwanda. The mature male silverback is on the left. A female and her offspring are in the middle, and an immature male is on the right.

Mountain gorillas are endangered. They are found only in small areas of Uganda, Rwanda, and the Democratic Republic of Congo. People there may lack basic resources such as food and clean water and may be desperate for cash to support their families. Gorilla babies and body parts can be sold for thousands of dollars. Gorillas can be killed for meat or caught in snares set to capture other animals. Any land that can be used for agriculture is in demand. Violence between warring groups is a chronic problem in the region, endangering anyone trying to protect the gorillas. These pressures and a slow rate of reproduction seemed to doom mountain gorillas to extinction.

This chapter will explore how human behavior contributes to environmental problems and also discuss strategies for changing human behaviors in ways that contribute to sustainability.

**Learning from the Case Study**

- What makes mountain gorillas vulnerable to extinction?
- How might human behavior have to change if gorillas are to be protected?

# Learning Outcomes

1. *Accurately describe how human behavior can cause environmental issues*
2. *Effectively analyze the roles of incentives, regulations, education, and appeals to emotion in influencing human behavior related to environmental issues.*
3. *Describe and evaluate the role of international cooperation in addressing environmental issues.*

**Vocabulary Toolkit**

**Opposites**

Internalized costs and externalized costs

**Word Watch List**

**Mitigation**: Effort to avoid problems or limit damage
**NGO**: Non-governmental organization (often not-for-profit)
**Intervention**: Attempt to become involved in a helpful way
**Incentives**: Rewards offered to encourage specific behaviors
**Subsidies**: Money used to reduce the costs of specific behaviors
**Externalized costs**: Costs that are not paid by those receiving benefits
**Unintended consequences**: Unpredicted events that happen as the result of an action
**Internalized costs**: Costs that are paid by those receiving benefits
**Anomaly**: Event that does not fit the general pattern
**Trend**: General pattern

**Human Behavior is the Key to Sustainability**

The first full-color photograph of Earth from space (Figure 2) is often credited with energizing the environmental movement of the late 1960s. On Earth, it is easy to imagine that there are no limits to what we can do to our planet. Viewed from space, our home looks like a rather fragile and isolated island of life in the cold, dark universe. Concern for protecting Earth did not begin with this photograph, but it did become more common for people to wonder whether the growing population of Earth should be changing its ways to protect its only home. This growing environmental awareness sometimes resulted in political change (see **Why It Matters: Environmental Progress is Possible**). People still disagree about how much environmental conservation is needed, and the best way to achieve particular goals, but most people want our planet to continue supporting human life indefinitely. People are also increasing their understanding that human health can depend on good environmental decisions (see **Make the Medical Connection: Human Impacts and Diseases**).

http://www.nasa.gov/sites/default/files/images/640273main_Apollo8-color-full.jpg

Figure 2. “Earthrise” taken on December 24, 1968 by the crew of Apollo 8.

**Why It Matters: Environmental Progress is Possible**

https://www.flickr.com/photos/ 97453745@N02/9305157863
https://commons.wikimedia.org/wiki/File:Cuyahoga_River,_Cleveland,_OH_%2828669489477%29.jpg

Figure 3. Cuyahoga River on fire in 1952 (left) and the much cleaner river in 2015 (right).

In 1969, the Cuyahoga River in Cleveland, Ohio was so badly polluted that it caught fire, causing over $50,000 worth of damage. The 1969 blaze was not even the first fire for the Cuyahoga. It had burned a dozen other times since 1868, costing lives and money. The Cuyahoga was not all that different from other many rivers at that time. Generations of Americans were used to dumping waste into rivers. It was a cheap and easy way to dispose of everything from sewage to industrial chemicals. But somehow media coverage and changing attitudes turned the last fire into a symbol for a larger environmental crisis that shocked many people into demanding action from their governments. As a result of this incident and others, enough political momentum was created to pass the 1970 National Environment Protection Act (NEPA) and the 1972 Clean Water Act.

Due to regulations that restrict water pollution, efforts of volunteers and professionals, and investment of funds from governments and NGOs, the Cuyahoga and most of America's urban rivers are now much cleaner than they were a few decades ago, even while urban populations have grown.

- Why is legislation on the national level needed to protect rivers?
- Which stakeholders might have been hurt by these environmental regulations?
- Are there additional regulations you would like to see or existing ones you would like to see removed?

**Make the Medical Connection: Human Impacts and Diseases**

The World Health Organization has identified many diseases that are influenced by environmental policy decisions (Table 1).

Table 1. Environmental activities that change the risks of human diseases.

| Environmental changes | Example diseases | Pathway of effect |
|---|---|---|
| Dams, canals, irrigation | Schistosomiasis | ▲ Snail host habitat, human contact |
| | Malaria | ▲ Breeding sites for mosquitoes |
| | Helminthiasies | ▲ Larval contact due to moist soil |
| | River blindness | ▼ Blackfly breeding, ▼ disease |
| Agricultural intensification | Malaria | Crop insecticides and ▲ vector resistance |
| | Venezuelan haemorraghic fever | ▲ rodent abundance, contact |
| Urbanization, urban crowding | Cholera | ▼ sanitation, hygiene; ▲ water contamination |
| | Dengue | Water-collecting trash, ▲ *Aedes aegypti* mosquito breeding sites |
| | Cutaneous leishmaniasis | ▲ proximity, sandfly vectors |
| Deforestation and new habitation | Malaria | ▲ Breeding sites and vectors, immigration of susceptible people |
| | Oropouche | ▲ contact, breeding of vectors |
| | Visceral leishmaniasis | ▲ contact with sandfly vectors |
| Reforestation | Lyme disease | ▲ tick hosts, outdoor exposure |
| Ocean warming | Red tide | ▲ Toxic algal blooms |
| Elevated precipitation | Rift valley fever | ▲ Pools for mosquito breeding |
| | Hantavirus pulmonary syndrome | ▲ Rodent food, habitat, abundance |

▲ increase ▼ reduction

http://www.who.int/globalchange/environment/en/chapter6.pdf

Most environmental issues are the result of some sort of human impacts, such as resource use, land alteration, waste production, or manipulating species. As Earth's population size increases, so do human impacts. Developing societies start to demand the lifestyle of developed nations, so the impact of each person increases. Sometimes these issues can be solved or made better—**mitigated**—through investments in research that provides technological solutions. However, technological advances are worthless if people do not adopt the new technology. Governments and **NGOs** (non-governmental organizations) must use a variety of strategies to influence human behavior if they hope to solve or mitigate environmental problems.

There are many barriers to changing human behavior. “We have always done this” is—for many people—a very good reason to continue doing something. Change is often seen as loss of something, and people avoid loss, whether it involves money, time, opportunity, effort, or freedom of choice. People may not believe that there is a need for change. Perhaps they have not heard about an issue, or they are convinced that the situation has been made up or exaggerated. Perhaps they believe that the proposed solution is either too drastic or the wrong approach. They may not even agree that the issue is a problem that should be solved. One person’s loss of an unspoiled wilderness lake is another person’s gain of a dream resort with all the modern luxuries.

Attempts to change human behavior—**interventions**—can come in various forms. Governments can regulate behavior, providing rewards—**incentives**—for some behaviors and punishing other behaviors through fines, loss of privileges, or imprisonment. Governments and NGOs can also influence behavior through educational or emotional appeals to people’s values.

**Check Your Understanding**

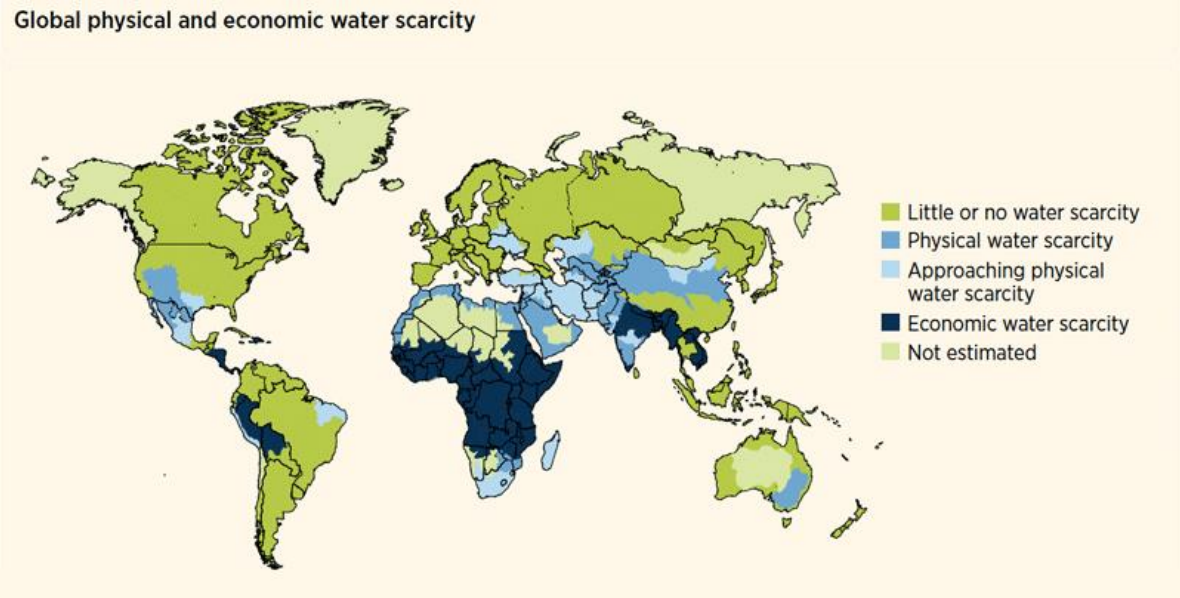
- How can human behavior contribute to environmental problems?
- What are some general approaches to changing human behaviors?

### Incentives and Self Interest Influence Behavior

Economic self-interest can potentially motivate people to conserve resources. For example, governments can control the use of resources by raising prices (tariffs and taxes) or by rewarding conservation. They could charge producers of waste high fees for disposing of that waste or give economic incentives for reducing waste.

Governments sometimes pay all or part of the costs of certain activities. These payments are called **subsidies**. They can take the form of direct payments, tax breaks, or reduced fees. For example, your city may encourage you to buy energy-efficient appliances by providing rebates or tax breaks. Subsidies are an example of **externalized costs**, in which the people or businesses that benefit from a practice do not pay the entire cost of the practice. For example, a city may add infrastructure (such as streets and services) to encourage businesses to build in a new area. Funds for the subsidies may come from taxes, fees, fines, or grants. Another type of externalized cost might not be obvious. For example, a company may sell “flushable” wipes that clog a city’s sewer system. The company does not pay for maintenance or repair caused by their product.

Depending on how they are used, subsidies can encourage either conservation or waste. Water scarcity is a major global issue (Figure 4). In the developed world, we use a lot of water. The US EPA estimates that an American family of four uses an average of 400 gallons a day for washing, flushing, and other activities. Agriculture and industry use huge amounts on our behalf.




http://www.un.org/waterforlifedecade/scarcity.shtml

Figure 4. Water scarcity. Physical water scarcity indicates that an area has little available water compared to the need for water. Economic water scarcity indicates that water is there, but there is not enough money to build systems for getting it to people.

It may seem that water is a renewable resource, but our use of water often moves it away from where it is needed. Storm, sewer, and excess irrigation water generally flow into surface water, eventually ending up in the sea (see Chapter 5). Some water evaporates from plants and surfaces, travelling with air currents. Products containing water may be shipped across the world. Some water is contaminated with wastes, making it unusable. While most of the United States does not yet have water scarcity, our aquifers are being drained much faster than they are being refilled, meaning that our water reserves are shrinking.

Governments have a long-term interest in ensuring sustainable water use, but government officials also have a shorter-term interest in satisfying the demands of citizens, campaign contributors, and other stakeholders who want cheap, plentiful food and water. This can encourage non-sustainable practices.

California experiences frequent water shortages that are predicted to get worse (Figure 5). Some communities use a structured set of household water fees to encourage conservation. If a household uses very little water, it pays a low rate per unit. As its usage rate increases, its per-unit costs increase. Some argue that the second (or higher) tiers should have even higher rates to discourage waste, but higher rates are not usually popular with voters.

https://earthobservatory.nasa.gov/images/148447/california-reservoirs-reflect-deepening-drought

Figure 5. The same area before and during a California drought.

80% of California's water is used by agriculture. Why are water-thirsty crops grown in a climate where drought is a problem? One reason is that the growing season is very long. Another is that federal and state government agencies subsidize the cost of water. Governments spend billions of dollars to build storage and delivery systems and pay millions of dollars to agribusinesses for buying efficient irrigation equipment. This equipment is then used to increase the size of fields, which means more use of the shrinking supply. It is a classic example of the Tragedy of the Commons (see Chapter 2). When the cost of the water is subsidized, there is much less economic motivation to conserve water. This may seem like an odd system, but stakeholder demand for low water and food prices encourages it.

**Check Your Understanding**

- Describe a way that government either uses or could use incentives to promote sustainable practices.
- What are some advantages and disadvantages to using self-interest as a way to influence human behavior?

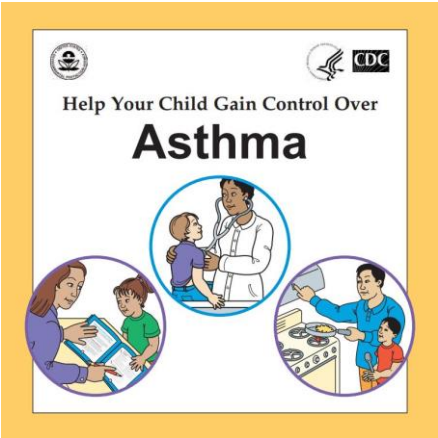
**Regulation Can Influence Human Behavior**

Resource use can be regulated directly through rationing. Under this system, consumers are allowed to use only a certain amount of a resource. If the government monitors the use, over-use of the resource can be punished. The punishment will usually be a fine, but some countries might use harsher penalties. Enforcement of regulations creates a new or increased cost to governments.

Limiting the supply of a resource can result in **unintended consequences**—results that were not predicted when an action was taken. For example, when international treaties outlawed ivory, ivory became scarcer and much more valuable. This created a black market for ivory, making poaching very profitable. Well-armed poachers now pose a major threat to the animals that were supposed to be protected by banning the legal trade in ivory.

Regulations can also be used to **internalize** costs. For example, a company may increase its profits by using methods that pollute. The costs of pollution are borne by an entire community. Some community members bear more of the costs than others (see **Make the Medical Connection: Asthma as an Environmental Justice Issue**). Regulations can require that a company meet specific standards, shifting costs back to potential polluters. An unintended consequence of this is the increased incentive for companies to dispose of potentially hazardous waste illegally. This lowers the companies' production costs. As a result, governments must spend money on enforcement to prevent illegal dumping.

**Make the Medical Connection: Asthma as an Environmental Justice Issue**




http://www.epa.gov/asthma/index.html

Figure 6. Part of a campaign to reduce asthma in children.

Recall from Chapter 2 that manufacturing, waste sites, and other sources of pollution are much more likely to be sited in low-income urban neighborhoods than in affluent suburbs. Older, cheaper housing is more likely to have mold issues and less likely to have effective air circulation and filtering systems.

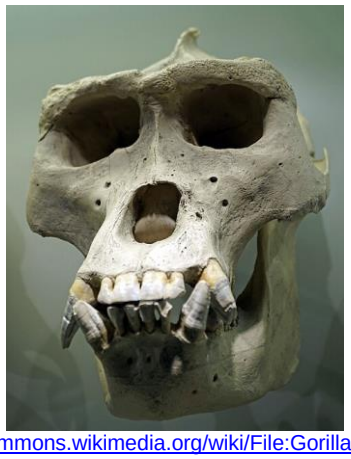
Children from lower-income homes and with non-white ethnicity in America are more likely to suffer from asthma than their peers. They have more additional health problems as a result. Poor health can trap future generations in poverty. Children with asthma are at risk for obesity and poor school performance, threatening their future health and employment options. Parents may face income or job loss as they care for ill children.

Individual activities can also be regulated to internalize costs. In many communities, businesses are required to charge a deposit on any new car battery or take an old battery in return. Discarded batteries can leak acid and heavy metals, contaminating soil and groundwater. The deposit system gives people an incentive to return their old battery for safe recycling or disposal. Car batteries only need replacement every few years, so these programs have a high compliance rate. Deposits on ordinary household batteries would probably be unpopular.

Many communities combine hazardous waste regulations with free disposal of household wastes to reduce illegal dumping. This externalizes the cost of disposal to all taxpayers. The programs may still be cost-effective in the long term because preventing contamination of water and soil may be much cheaper than cleanup. Unfortunately, the short-term cost is much more visible than the long-term benefit.

Regulations must often balance the interests of multiple stakeholders and must be flexible enough to gain popular support. If they are too restrictive, they may never be enacted, or backlash from voters may remove them.

### Case Study Part 2: Failures in Gorilla Conservation



https://commons.wikimedia.org/wiki/File:Gorilla_skull.jpg

Figure 7. Gorilla skull.

When foreigners started suggesting that the African nations of Uganda, Rwanda, and the Democratic Republic of Congo should conserve the mountain gorillas, local people were resentful of outsiders telling them how to manage their resources. Early conservation efforts focused on legal protection for gorilla habitat. Forests that had been a source of resources for local people became national forests where hunting and harvesting wood for fuel was forbidden. Residents often felt that conservation efforts prioritized gorillas over people. Without the support of local communities, enforcement of regulations was difficult. People not only continued to set snares, but they also set fires. Rangers were no match for the heavily armed soldiers who took refuge in the mountains during the violent conflicts in the region.

### Learning from the Case Study

- Why did initial enforcement efforts fail?
- How might the values of various stakeholders differ or be similar?

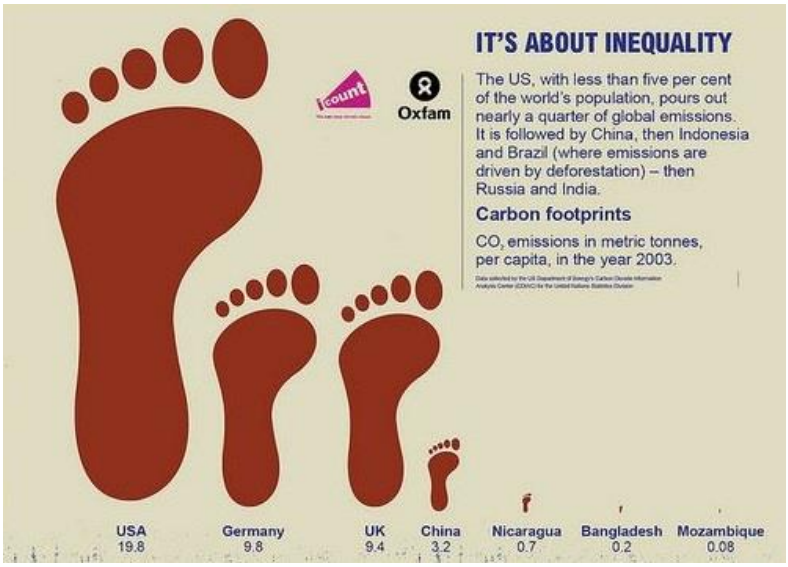
### Check Your Understanding

- Describe a way that government either uses or could use internalization of costs to promote sustainable practices.
- What are some advantages and disadvantages to using regulation as a way to influence human behavior?

**Education Changes Behavior if Barriers are Low**

Another strategy for changing behaviors is to educate people about the consequences of those behaviors. Education is one of the tools currently used to try to decrease greenhouse gas emissions that contribute to global climate change.

Many public education campaigns have the goal of increasing people's awareness of their "carbon footprint"—the amount of atmospheric carbon produced by their activities (Figure 8). Providing information may not be enough to produce more than small behavioral changes, but education campaigns can also be used to publicize incentives and regulations or can be combined with appeals to people's values.




https://www.flickr.com/photos/wheatfields/2948688445/

Figure 8. Example of a poster used to educate people about their carbon footprint.

**Analyze the Figure**

- How does the poster attempt to use education to change human behavior?
- What elements might make this poster effective?

**Misconception Alert: Education is an effective method of changing behavior**

**FALSE.** Merely telling people about an issue is unlikely to change their behavior unless the change is very easy. If the new behavior takes much time, effort or money, education alone is rarely effective. However, combining education with other strategies may be effective.

**Check Your Understanding**

- Under what conditions is education likely to result in increasing sustainable practices?
- What are some ways to improve the impact of education campaigns?

## Appeals to Values can Influence Behavior

If a government or NGO can connect behaviors with values, they may be able to change the behaviors. Media campaigns that show the devastating effects of environmental problems and the difference that your behavior makes are common. Of course people value many things, and each individual has a hierarchy of values. A person might dislike toxins in water but still be unwilling to take unwanted household chemicals across town to dispose of them safely. Another person might value clean air but be unwilling to pay more for a vehicle that has lower emissions. An effective appeal will target multiple values. Look back at Figure 8. It compares the large carbon footprint of US residents with those of other countries. This is an attempt to appeal to the sense of justice of people who may already know that a large carbon footprint is an environmental problem.

Every community has behavioral norms. These are informal rules about acceptable behavior. They can be changed directly or used to change behavior. Some approaches appeal to people as good community members. For example, a PSA might state that you are already taking several important steps and encouraging you to continue to do more. The hidden message is that everybody does these good things. If you value the opinion of your peers, you will do them too. Implying that something is a social norm can make it one if the message is effective. Consider how you might use various techniques to improve an existing PSA (see **Do Try this at Home: Public Service Campaigns**).

**Do Try this at Home: Public Service Campaigns**

Find a PSA, poster, or other media item promoting an action related to the environment. Analyze it for its effectiveness. Think about the many elements it uses and whether these elements are likely to be effective in changing people's behavior.

What information does it supply? Is it clear? Can you find and evaluate the data for accuracy and bias? What value appeals does it include? Does it suggest that everyone in your community is behaving better than you are, or does it suggest that you behave better than your neighbors? Does it suggest that you will save money, promote justice, preserve popular species, enhance the lives of future generations, or improve your health? Does it make connections between spiritual values and environmental behavior? What aesthetic decisions (use of color, sound, fonts, formatting, and word choice) did the creators of this piece use to increase the effectiveness of the message?

How would you improve this item or campaign to make it more effective?

**Hypothesis Testing: Do Humans Benefit from Connecting with Nature?**

> *Perhaps our grandsons, having never seen a wild river, will never miss the chance to set a canoe in singing waters.*
>
> Aldo Leopold

Do humans benefit from time in the natural environment? Our ancestors were much more likely to live on farms or in rural areas than we are today. Children of today are spending more time on electronic activities and less time recreating outside than their parents and grandparents did. They may be kept inside due to perceived dangers or be participating in more organized activities. Researchers wondered whether experiences in nature were beneficial to the mental health of young people.

Hypothesis: Adolescents would have improved mood after experiences in nature.

The researchers asked young people to score themselves subjectively on a stress scale (VAS) from 1-10. Then the subjects were randomly assigned to watch a 10-minute video that simulated either a walk in nature or a ride on an underground train. After the video, they scored themselves again (Figure 9).

Figure 9. Mean stress levels of adolescents before and after simulated natural or urban experiences. Means with the same letters are not significantly different. Based on data from: Chang, C. C., Lin, B. B., Feng, X., Andersson, E., Gardner, J., & Astell-Burt, T. (2024). A lower connection to nature is related to lower mental health benefits from nature contact. *Scientific Reports*, *14*(1), 6705.

**Analyze the Figure**

- Did the simulated woodland walk significantly reduce stress?
- Did the simulated train ride significantly reduce stress?

**Evaluate the Hypothesis**

- Was the hypothesis supported by these results?
- What information would help to evaluate the hypotheses further?

**Check Your Understanding**

- Describe some advantages and disadvantages to using appeals to values to promote sustainable practices.
- Would the same values appeal be effective to multiple stakeholders?
- How might experience with nature influence mental health?

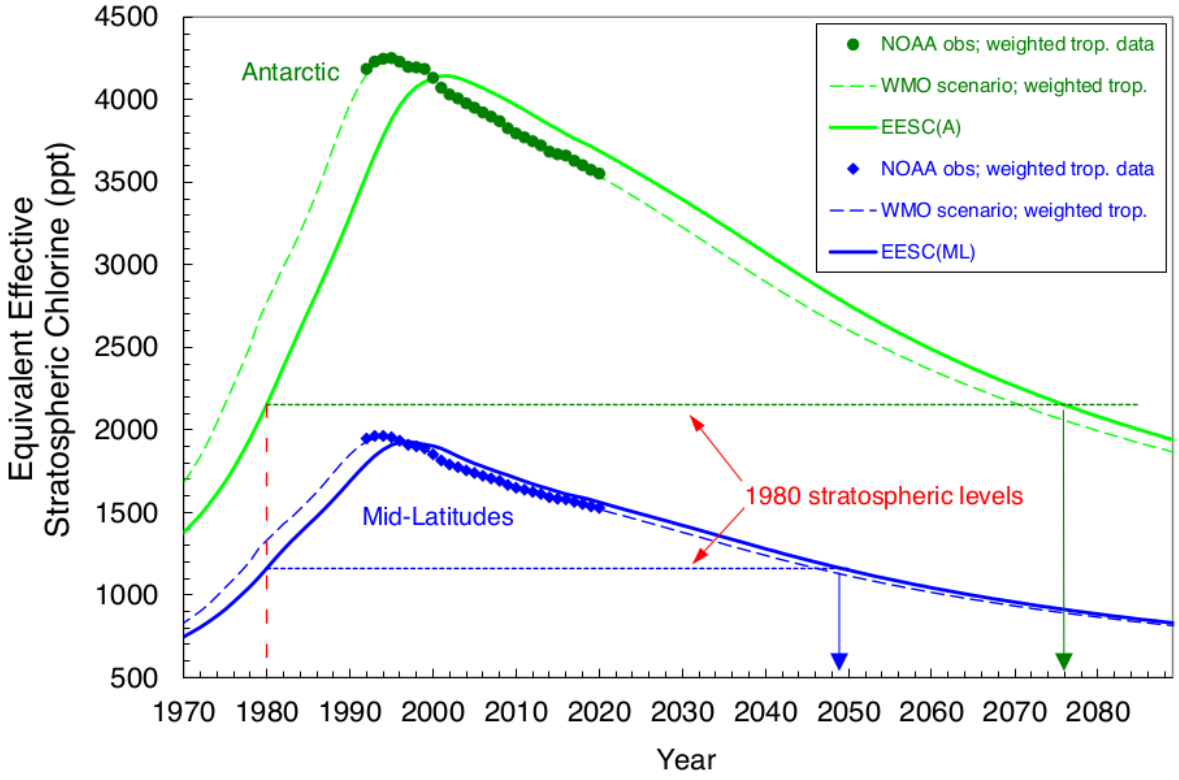
## Some Environmental Issues Require International Cooperation

Nations can create agreements or treaties to voluntarily protect global resources. International agreements have been used to address issues such as overfishing in the oceans, climate change, air pollution, nuclear waste, whaling, biodiversity, and ozone depletion.

Ozone is harmful when it is in the lower atmosphere, but in the stratosphere (10-50 km above the ground) it protects us from harmful rays of the sun. The size of the ozone layer varies in time and space. In the late 1970's scientists raised concerns about the thinning of the ozone layer, especially over the poles. A thinner ozone layer means higher rates of skin cancer, cataracts (damage to the eye), and depression of the immune system. It may damage plankton in the photic zone of the ocean and plants on land, leading to lower global productivity. It can also increase heating of Earth by the sun.

Chemicals used in aerosol spray cans and refrigeration units were the primary cause of ozone loss. Use of ozone-depleting substances (ODS) anywhere in the world damages the ozone layer. Ozone damage can affect any country in the world. Part of managing such a complex problem is determining what will happen in the future under a variety of scenarios (**Model Skill: Making long-term predictions**).

Developed countries agreed to restrict or eliminate the use of these chemicals under the 1987 United Nations Montreal Protocol for Protection of the Ozone Layer. The chemicals last a long time, but their levels have started to drop (Figure 10). If nations had not voluntarily agreed to limit these chemicals, the situation would be much worse.




https://gml.noaa.gov/odgi/

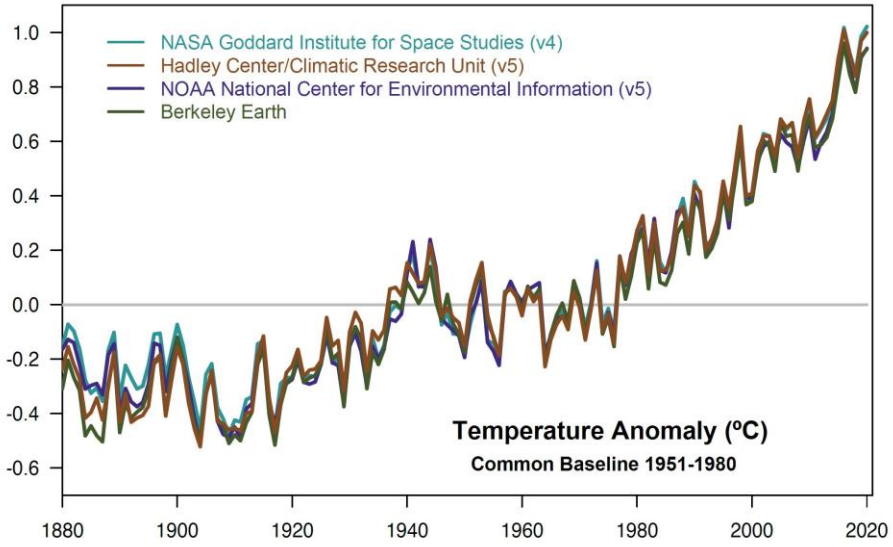
Figure 10. Measurements and predictions of ozone-depleting substances (ODS) in the stratospheric level of the atmosphere in the Antarctic and mid-latitudes. ODS production was reduced by the 1987 international agreement. Dots mark specific data points. Lines after 2020 reflect predictions from different scenarios that assume different levels of compliance with agreements.

**Analyze the Figure**

- According to the predictions, will ozone concentration reach 1980 levels by 2050?
- Which predictions are more likely to be accurate, those for 10 years in the future, or for those 50 years in the future? Why?

**Model Skill: Making Long-term Predictions**

By definition, predictions require drawing conclusions beyond the range of current data. This does not mean that all predictions are equally valid. A reasonable prediction uses known data and patterns to extrapolate the most likely future pattern. For example, Figure 11 shows variation in global surface temperature patterns. An **anomaly** is a data point or set that is higher or lower than the expected value. As you can see, there was a lot of variation in annual average temperatures between 1880 and 2020. However, it is also obvious that there is a warming **trend**, or general pattern. This does not mean that there were no unusually cold years. The data are global averages, so it is also possible that some locations on the Earth might be cooler than they were in the past.




https://www.giss.nasa.gov/research/news/20210114/temp-2020_comparison-plot-1.jpg

Figure 11. Deviations from average annual global temperatures (solid gray line). The four data lines represent different observatories.

**Analyze the Figure**

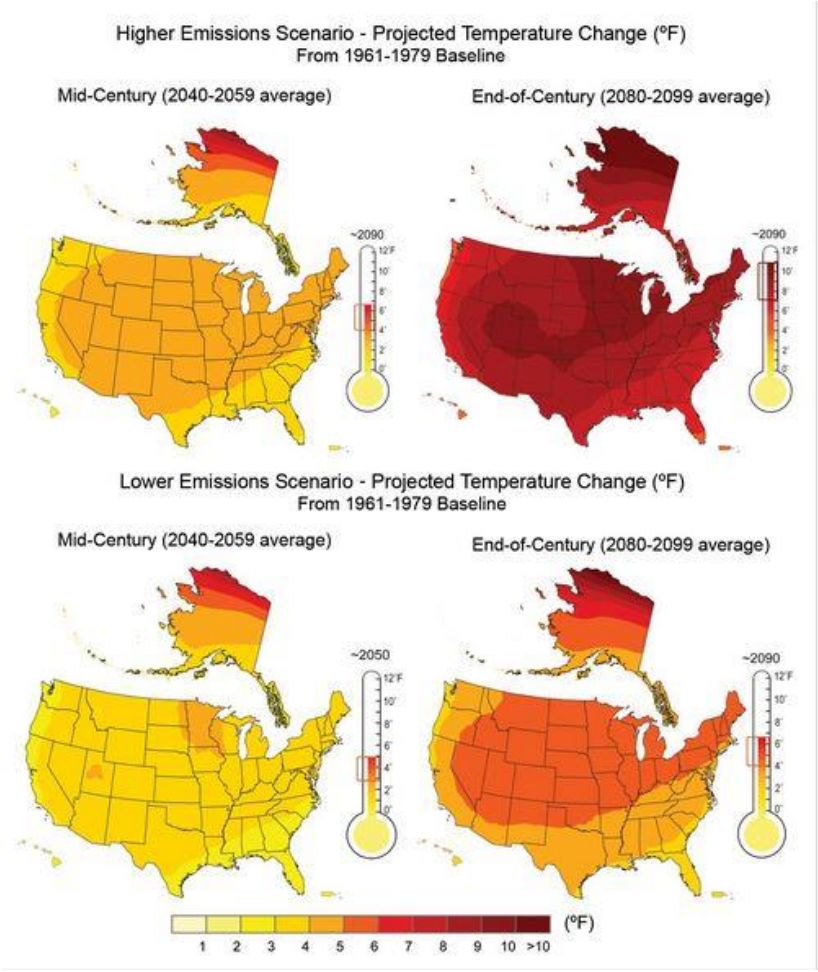
- What year in this data set showed the lowest average annual temperature?
- Would the average annual temperature for the entire data set be greater or lower than the average for 1981 to 2010?

Predicting future changes in temperature (Figure 15) requires identifying the variables that cause warming, quantifying them (putting numbers to them), and putting them into a model that predicts the relationship between the variables that influence temperature (such as carbon production) and temperature.

**Continued**

**Model Skill: Making Long-term Predictions, Cont.**

These models are complex, requiring supercomputers. Researchers also have to make predictions about how the variables will change. Will there be more people? Will the individual carbon footprints be increasing or decreasing? The farther into the future the predictions are, the more uncertainty there is about their predictions.




http://www.epa.gov/climatechange/science/future.html

Figure 12. Predictions of temperature change in the United States. The Upper diagrams represent predictions based on the assumption that greenhouse gas emissions will remain high. The lower diagrams represent predictions that greenhouse gas emissions will decrease.

**Analyze the Figure**

- What regions will have the greatest increase in temperature (not the highest temperature)?
- Which regions will be influenced most by emissions levels by mid-century?

Global cooperation is not always possible. Some countries may not be willing to cooperate with the global community and others might be willing, but lack the resources. Some developed nations have decided that it is in their own best interests to subsidize the efforts of countries with fewer resources. No country is so isolated that they are not influenced by the environmental decisions of other countries. As the human population expands, and the environmental footprint of each individual expands, humans can not afford to ignore our influence on all living things (see **Evolutionary Perspective: Will Human Activity Cause the Next Extinction Cycle?**).

**Evolutionary Perspective: Will Human Activity Cause the Next Extinction Cycle?**

Recall from Chapter 17 that there have been many cycles of extinction and increasing diversity in Earth's history. Humans have caused extinctions in the past. Some predict a larger wave of human-caused extinction in the future.

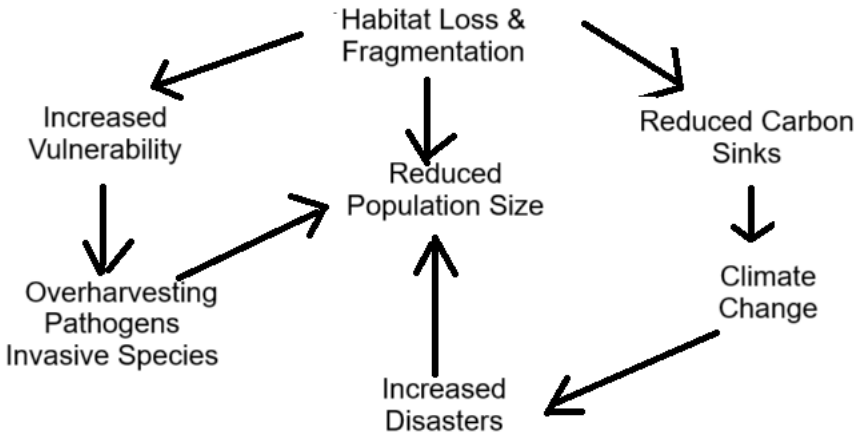



Figure 13. Model of interactions between threats to biodiversity. Simplified from: Brook, B. W., Sodhi, N. S., & Bradshaw, C. J. (2008). Synergies among extinction drivers under global change. *Trends in ecology & evolution*, *23*(8), 453-460.

**Analyze the Figure**

- According to this model, what are some of the greatest threats to biodiversity?
- How might some of these threats interact?
- Are there connections that you would add to this model?

**Case Study Part 3: A Comprehensive Plan for Gorilla Conservation**

Burton 2008

Figure 14. Sign in Rwanda reminding citizens of the value of peace and gorillas.

Successfully protecting the gorillas required the use of multiple strategies across borders. Governments and NGOs began to concentrate on programs that would protect the animal and benefit the local people. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) helps prevent smuggling of baby gorillas or gorilla parts. The United Nations is sometimes needed to keep peace in the area. Laws were passed to create protected areas and prevent hunting.

Plans became focused on making live gorillas more valuable than dead ones. International tourism provides some of the funding. High fees ($1500 per person per day in Rwanda) are charged for tourists to visit the gorillas. Some of the money is used to equip and pay rangers and soldiers who protect the gorillas. International NGOs supplement the salaries of rangers. Guides and local businesses profit directly from gorilla-watching tourism, enriching the local economy. Other income-generating projects include agricultural and tourism facilities that allow former poachers to provide for their families without killing wildlife.

Local communities decide how their share of the tourism money will be used. One constant concern in the region is obtaining water. Water must be purchased, then carried on foot or bicycle in 5-gallon plastic cans. It is not easy to transport 40 pounds of water in this mountainous region. Some communities invest in water tanks for schools. This allows children to get their education and their families' water in the same place. Another village might invest in educational or medical supplies.

Public relations campaigns are used internationally to appeal to people's conservation values and locally to promote the idea that gorilla protection benefits the community (Figure 14). The combination of international agreements, economic incentives, regulation, and appeals to values has been successful. Mountain gorillas are still endangered and face multiple threats, but populations are slowly increasing. This coordinated approach may provide a model for protecting other species.

**Learning from the Case Study**

- How does the concept of internalizing benefits apply to this program?
- Do you think that the efforts to conserve mountain gorillas fair, economically feasible and environmentally sustainable? Give evidence to support your answer.

**Check Your Understanding**

- Why is international cooperation required to address some environmental issues?
- What are some of the potential problems involved with actions that require international cooperation?
- Why might it benefit one country to help other countries with their environmental problems?

# Key Concepts

- Human activities such as unsustainable resource use, land alteration, waste production, and species manipulation may cause environmental problems.
- Incentives such as subsidies can encourage better environmental practices by externalizing costs, but the long-term benefits may be less obvious than the short-term costs.
- Regulation can change resource use and disposal, but enforcement can be difficult and expensive. It can also lead to unintended consequences.
- Education can raise awareness of issues, but it is usually not enough to overcome barriers in changing behavior unless combined with other strategies.
- Appeals to values can be persuasive. Competing values can make it difficult to resolve environmental issues.
- Combining multiple strategies can be effective in changing human behavior
- International cooperation may be necessary to address some environmental problems.

# Apply the Concepts

**Learning Outcomes**

1. *Accurately describe how human behavior can cause environmental issues*
2. *Effectively analyze the roles of incentives, regulations, education, and appeals to emotion in influencing human behavior related to environmental issues.*
3. *Describe and evaluate the role of international cooperation in addressing environmental issues.*

1. Electronic devices such as computers and cell phones contain heavy metals and other toxic wastes. Discarded technology (often called “e-waste”) in landfills can contaminate soil and water. Safely recycling the hazardous waste is expensive. Some e-waste is sent to developing nations where it is scavenged for raw materials under conditions that poison the environment and the workers.

   A. What specific behaviors by consumers in developed countries cause the e-waste problem?
   B. How could the cost of safely disposing of e-waste be internalized to influence consumer behavior?
   C. How might international cooperation help to address the e-waste issue?
   D. If you were designing a campaign to reduce e-waste, what messages would you include? *(Learning Outcomes 1-3)*

2. Refer to Figure 15.

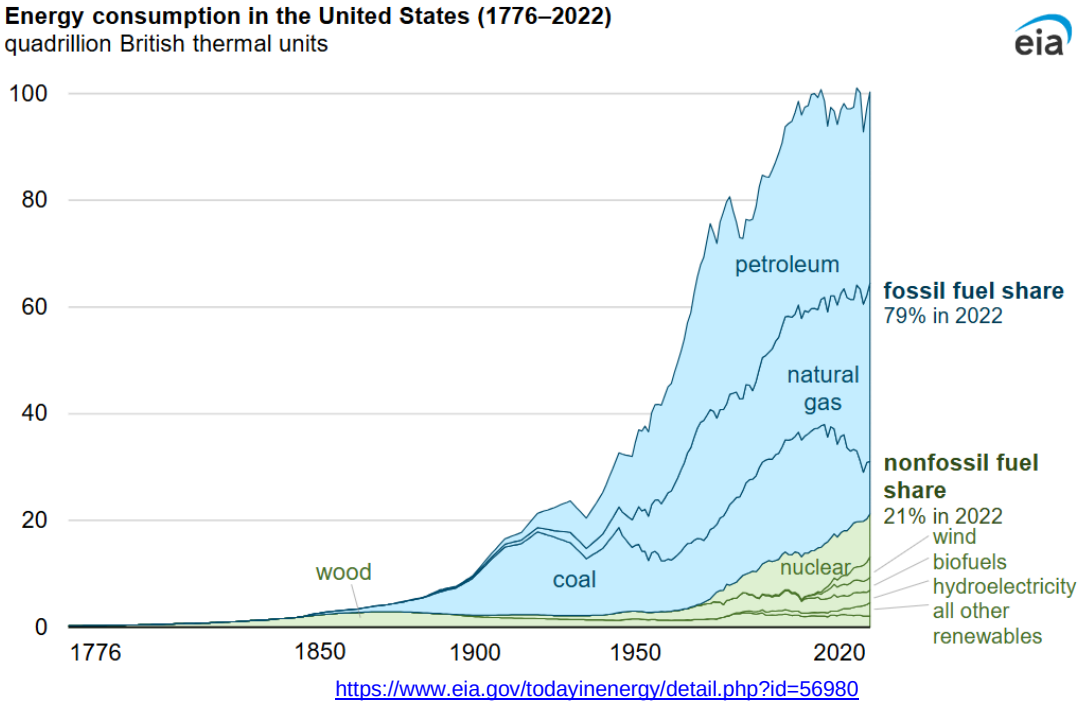



Figure 15. Total energy consumption in the United States.

A. Identify some of the individual behaviors that result in oil consumption in the US.
B. Which of those behaviors do you think will change in the next few years? Will they increase or decrease? Explain your reasoning.
C. If you wanted to decrease oil consumption by the US, what is one strategy that you think would be effective? Explain your reasoning. *(Learning Outcomes 1 & 2)*

3. The government of Quito, Ecuador tried to reduce driving by using license plate numbers to determine which days people were allowed to drive. Many families purchased a second car with a different license plate to drive on the days they were not allowed to drive their primary car. The second car was often older and produced more emissions. This is an example of:

A. Failure of an education program due to high barriers.
B. Failure of an appeal to values program because people like to drive.
C. Failure of regulation due to unintended consequences.
D. Failure of an incentive program because rewards were too low.
*(Learning Outcomes 2)*

## Appendix A
## Reading Primary Literature

Sources

**Primary sources** are articles or reports written by the people who conducted the research. Summaries citing primary sources are called **secondary sources**. **Tertiary** sources are based on secondary sources. With each step away from the original source, errors can creep in. Even accurate information may be simplified.

**Peer-reviewed** articles are evaluated by other scientists before they are published in academic journals. Reviewers determine whether the experiment was conducted and communicated appropriately. Peer-reviewed papers are not perfect, but they are the best source of accurate scientific information. Primary articles can be intimidating at first. This appendix will help you read the primary literature of any scientific field efficiently and effectively.

As you read, highlight the main ideas, and write your own questions and notes. Identify words to look up. You may have to read sections two or three times before you really understand them. Expect to spend much more time reading a page of a technical article than you do on a page of a textbook.

Look at the title and read the **abstract** (summary) to get the main ideas of the paper. Note the date of the article.

Organization

Read the **introduction**. It will set context about what is known about the topic and why this experiment was done. Note what is known about the species or system. It will state the general question and hypothesis or hypotheses.

Read the **methods** section. Note sample size, possible confounding variables, and controls. Sketch a map of the methods if the design is complicated.

Read the **results** section, paying attention to the figures and tables. Identify trends and outliers. Were the results statistically significant? How would you explain the patterns you see?

Read the **discussion** and **conclusions** to see the authors' explanations for the patterns in the data. Analyze the arguments carefully. Honest, well-informed people can have different views on what the data mean. You must decide which conclusions the evidence supports. What experiment would you do next?

## Appendix B
## Designing Experiments

Without valid experimental design, research tells us nothing. Use this guide to design effective experiments. Check with your instructor before beginning to make sure that your proposed experiment is safe, ethical, and legal. Decide on a statistical test before you start. Careful planning results in a better experiment.

Hypotheses

A **hypothesis** is a general statement with the power to explain patterns. For example, "It will be cooler above the dark soil than the light soil because darker soil absorbs more heat than light soil" is a hypothesis. It contains an explanation. It could apply to soil anywhere. "It will be cooler 5 cm above the dark soil than the light soil" is a **prediction** of what you expect to find if your hypothesis is correct. Hypotheses must be **falsifiable**. Your experiment could contradict your hypothesis. Your experiment may support your hypothesis, but it cannot prove your hypothesis correct because there may be other explanations for the same findings. Predictions are a statement of what you *expect*. Hypotheses are *explanations* for observations.

In any experiment, the statistical **null hypothesis** states there is no difference between the groups, or no effect of the potential independent variable. In this case, the null hypothesis is that soil color does not influence air temperature. Two **alternative hypotheses** would be that air temperature will be cooler over dark soil than light soil and that air temperature will be warmer over dark soil than light soil.

Identifying variables

Soil color is the **independent variable**. Air temperature is the **dependent** or **responding variable**. Independent variables influence dependent variables. Changing the soil color may influence the temperature, but the air temperature will not change the color of the soil. The difference between dependent and independent variables is not always this clear. Pine trees may make soil more acidic, but pine trees may also grow better in acidic soil.

Manipulating variables

If your question were whether adding nitrogen to soil increased growth of a plant, you would compare your **experimental group** (those given extra soil nitrogen) with a **control group** (no extra nitrogen). Your experimental groups must differ only in the one independent variable that you are measuring. For example, you would not put the nitrogen-added plants closer to the window than the control plants. Variables that create additional differences between the groups are called **confounding variables**. If your experiment has them, nothing can fix your results later.

Sample Size

Sample size is the number of independent replicates in your experiment. If you had 20 pots containing plants, your sample size would be 20. If you had one pot with 20 plants, your sample size would be one. The natural world contains a lot of variation. Individuals in a species differ from each other. Locations differ in temperature, humidity, soil, and many other variables. A well-designed sample must contain several individuals or sites in each of the groups you are comparing and they must be independent of each other.

Randomization

**Randomization** reduces bias and confounding variables. Every individual in a population must have an equal chance of being sampled. For example, if you grab the first 10 plants off the shelf to supplement with nitrogen, you may have chosen the plants that were largest or healthiest because they were nearest to the light. However, you cab flip a coin to randomly assign each plant to a group. In behavior studies, your results may depend on which individual you choose to observe. For example, if you choose the first animal you see, your results may only be true for the individuals that are easiest to see. A population could also be the total number of possible sites. Then you need a method for choosing individual sites. This can be done using coordinates or transects, for example.

Protocols

Plan your methods carefully to avoid bias. Decide on guidelines for what data will be gathered, when it will be gathered, and exactly how you will measure. For example, will you measure plant height at the highest point, or will you lift the tip of the plant if it is drooping? This would be your experimental **protocol**. As you collect data, make notes about anything that may have influenced your results. Do not assume that you will remember an event without writing it down. Keep very accurate and detailed notes.

See Appendix C for Analyzing Data and Appendix D for graphing data.

## Appendix C
## Analyzing Data

This guide is no substitute for a course on statistics. There are many statistical analyses possible, but the tests described here will usually allow you to analyze data gathered in an ecology laboratory class.

Descriptive statistics

One major summary statistic is a measure of the central tendency of the numbers, such as a mean (average), median, or mode. The second is a measure of how different the numbers are, which is measured using standard deviation, standard error (the standard deviation divided by the square root of the sample size), or variance.

T tests

T tests are used to compare two groups or treatments, generically called populations. The question you are asking is whether the populations you're sampling from are actually different. If the means of your samples are different enough, given the variation in your sample, that is evidence that the populations are different.

To decide whether you should do a "one-tailed" or "two-tailed" test, remember your prediction about the direction of the difference between the groups. If you predicted group A would be lower than group B, or B would be lower than A, pick 1 tail. If you didn't predict which would be higher, use 2 tails. You can't change your mind after the data are gathered.

Next decide whether your groups are paired (dependent) or unpaired (independent). If you tested whether pH in lakes was higher during the day or the night, you would be comparing the pH of the same lakes under two different conditions. This would require a "paired" or "dependent" T test.

If you tested whether lakes in your county had a different pH than the lakes in a county 100 km south, you would then have two groups of lakes rather than taking 2 measurements on each lake. You would use an "unpaired" or "independent" T-test.

A P-value below 0.05 is generally considered statistically significant, while one of 0.05 or greater indicates no difference between the groups. One way to think of a P-value is that it is the probability that you are *wrong* when you say that the groups are different. The lower the P-value, the higher the probability that the populations are different.

Correlations

Use correlations to look at whether changes in one variable are accompanied by changes in another variable. For example, let's say you wanted to know whether the number of fish species in a lake were related to the size of the lake. A correlation test will provide an R or $R^2$ value. A "1" would mean complete correlation. A "0" would mean none. A negative number means that when one variable goes up, the other goes down. A positive number means they rise and fall together. Remember that correlation does not prove causation.

Chi Square Test

Use the chi (pronounced “ky” as in “sky”) square test to look at whether actual data differ from a random distribution. For example, say you want to find out whether parrots prefer particular types of food. Assume there are five different types that the parrots are familiar with and the types are presented at the same time. You would test the parrots separately and record the first type eaten by each parrot. If parrots chose at random, the proportion of each food chosen first by the test parrots would be equal (food A would be chosen first about 20% of the time, food C would be chosen first about 20% of the time, etc.). You might find that 19% of the time parrots chose food A and 21% of the time they chose food C, but when do you have enough evidence to say the parrots are choosing them non-randomly? This test will tell you.

First you will put your actual data in one row. Enter the numbers (not percent) you observed. For example, under food A, you would enter the number of times it was chosen first. In the "Expected" row, enter the number you would expect to find if the selection were random. In our example, we had five food types, so we expect to find that each food type was chosen first in 20% of our total trials if parrots were choosing randomly. Multiply the total number of parrots by 20% to get the expected number for each food type. Note: the test assumes that each choice is independent, so for this test to be valid, you would have to make sure that you used different parrots, each of which was tested by itself.

Depending on the statistical program you use, the test may provide a P-value or a chi-square value. In our case, the P-value is the probability that parrots are choosing food randomly. The smaller the number, the greater the likelihood that they are choosing by food preference. Remember that a P-value below 0.05 is generally considered statistically significant, while one of 0.05 or greater indicates the distribution is random.

## Appendix D
## Understanding and Creating Graphs

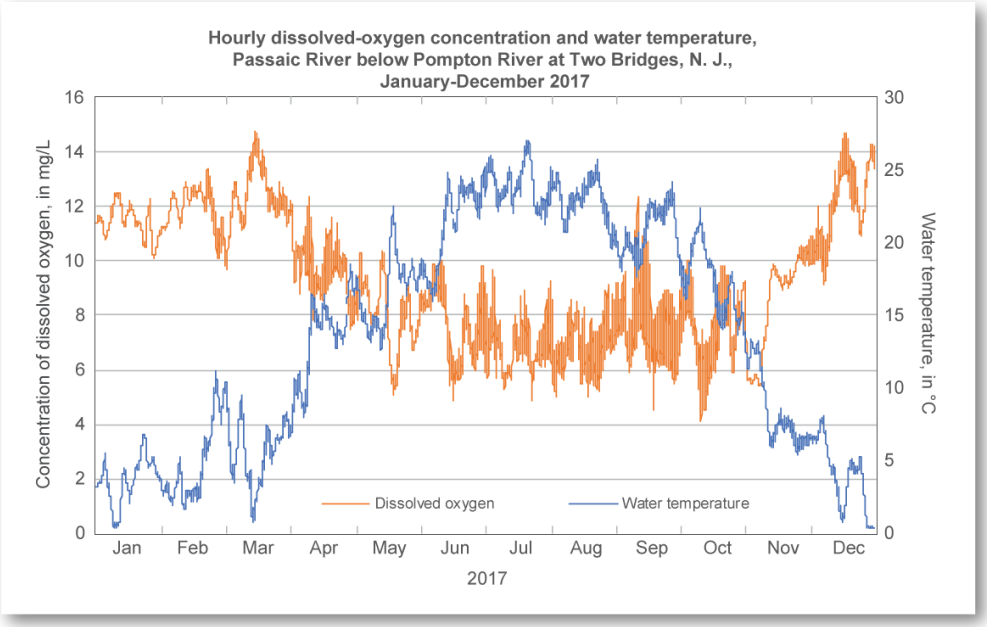
### Graph Types

A properly constructed graph will tell the story of your data clearly and quickly. A reader should be able to understand your results without reading the text. Effective graphs require careful design. Graph design is covered in more detail within various chapters.

First, decide on the main message of your graph. Next, determine the appropriate graph type for your data. There are many types of graphs, but most ecological data can be properly represented in one of the formats described below.

Changes over time

Use a line chart if your data involve a timeline, such as days after treatment, life stages, or seasons (Figure 1). Do not use this type of graph for correlation analysis.




https://www.usgs.gov/media/images/temperature-affects-dissolved-oxygen-concentrations

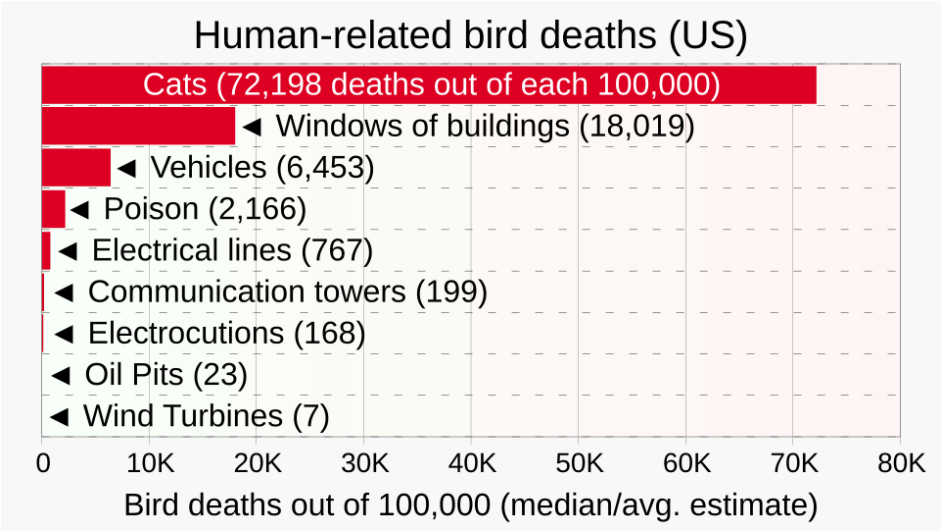
Fig1. A line chart, used for data that change through time. The use of two Y axes allows comparison of two types of data with different units and scales.

### Analyze the Figure

- What was the approximate maximum water temperature in the river during this time?
- What was the approximate minimum level of dissolved oxygen?
- Use a sentence to describe the most important pattern that you see.

Comparisons Between Categories

Use a bar/column or box and whiskers chart if your data involve counts or amounts in discrete categories, such as species, conditions, or locations. Some categories might have a natural order, such as distance from the equator or successional stage. Otherwise, categories might be ordered by their values, such as number of deaths or amount of rainfall. Figure 2 has counts for categorical data. It is best shown as either vertical or horizontal bars.




https://commons.m.wikimedia.org/wiki/File:2017_Human-related_causes_of_bird_deaths_%28US%29.svg

Figure 2. A bar or column chart, used for data that are sorted by categories.

**Analyze the Figure**

- What was the leading cause of human-related bird deaths?
- Approximately what percentage of human-related bird deaths are due to collisions with windows of buildings?

When a bar or column chart is used to show a mean, add a measure of variation, such as standard error or standard deviation using error bars.

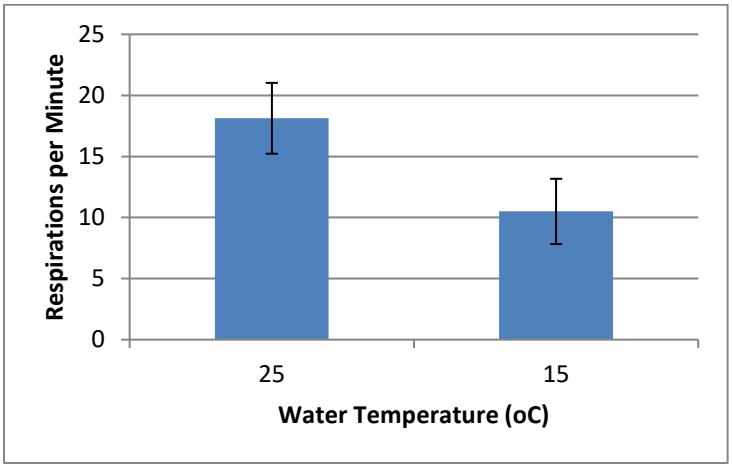
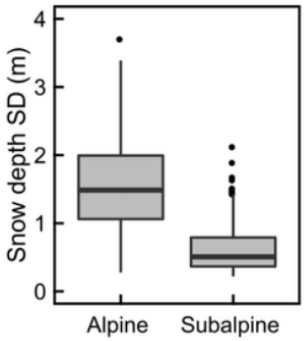



Figure 3. Column/bar chart. Error bars indicate variability around the mean. No title is used unless it is in a presentation or if one figure contains multiple graphs. The caption must include information on what the error bars show, for example, Mean (+/- S.E.)

**Analyze the Figure**

- What was the average number of respirations per minute were observed at 25 $^{o}$C?
- Approximately what percentage of human-related bird deaths are due to collisions with windows of buildings?

A box and whisker plot is used for categorical data to highlight variation.




https://www.researchgate.net/figure/Boxplots-showing-the-outliers-black-circles-10th-and-90th-percentiles-whiskers-25th_fig4_310818913

Figure 4. Box and whisker plots showing medians (dark lines), quartiles (limts of boxes), 10$^{th}$ and 90$^{th}$ percentiles (end of whiskers) and outliers (markers).

**Analyze the Figure**

- Which area had greater variation in snow depth?
- Why would variation above the median be greater than below for this data set?

Correlations

Use an XY graph (scatterplot) to show the effect of one variable on another (Figure 5). Put the independent variable on the X-axis. The line on a scatterplot does not connect the data points. It is a model that presents a simplified picture of the data. It may be a linear model, as seen in the example, or follow some other function. The $R^2$ value is the strength of the relationship between the variables using this model. Correlations are discussed further in Appendix C.

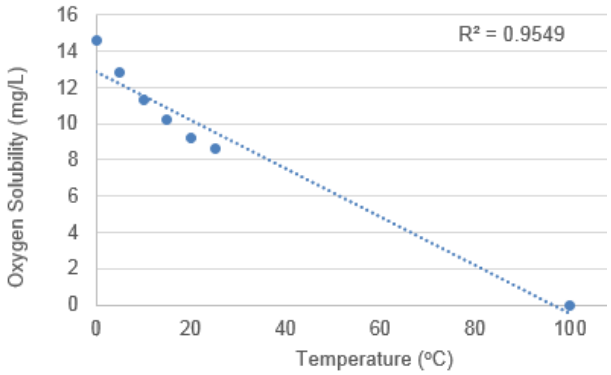



Figure 5. XY graph or scatterplot showing the relationship between water temperature and oxygen solubility.

**Analyze the Figure**

- What is the approximate oxygen solubility at 20 °C?
- Predict the oxygen solubility at 50 °C.

Proportions of a Whole

Use a pie chart if your data show how much each part contributes to a whole, using counts, amounts, percentages, or proportions (Figure 6). If using black and white, using the boldest patterns for the smallest proportions make them easier to see.

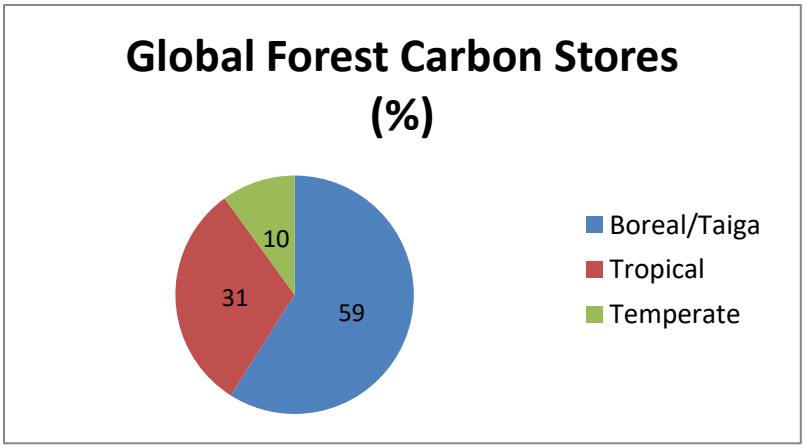



Fig 6. A pie chart shows how parts contribute to a whole.

**Analyze the Figure**

1. Which type of forest stores most of the carbon?
2. Does this graph tell you how much carbon is stored in the world's forests?
3. How much more carbon is stored in tropical forests than temperate forests?

## Using a Logarithmic Scale

If the values on one or both axes have a very broad range, a logarithmic (log) scale can be used. Each of the major intervals is 10 times as big as the one below it. It starts at 1 on the bottom, and goes up by ones. Then at 10, it goes up by tens. At 100, it goes up by hundreds.
For example, 1,000 = $10^3$. So on a log scale, 1,000 is written as 3. Ten thousand would be written as 4 because $10^4$ =10,000.One is written as 0 because $10^0$ = 1. There is no zero on a log scale.

A comparison of two graphs showing the same data demonstrates situations in which a log scale is useful (Figure 7).

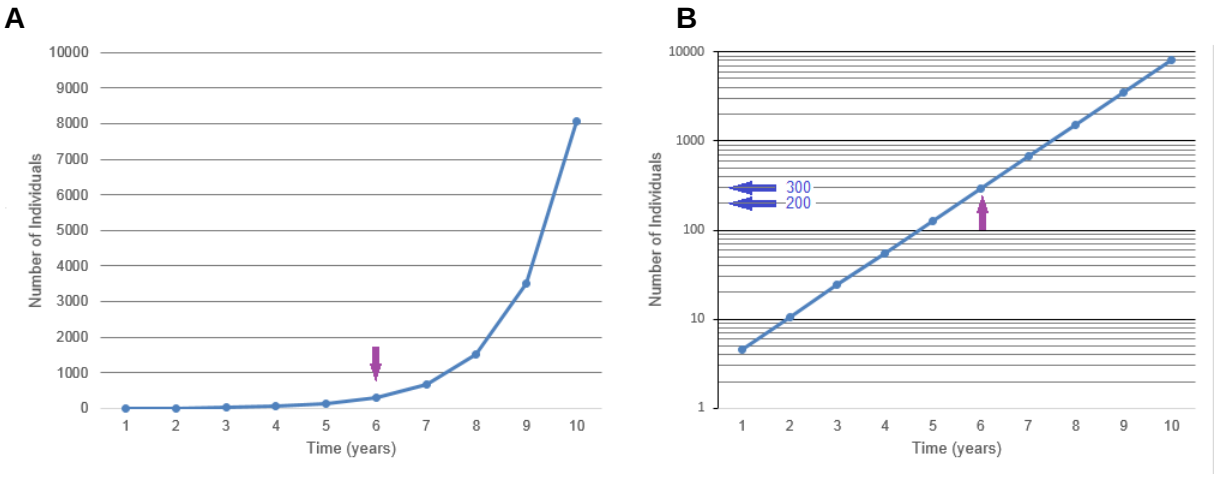



Figure 7. Comparison of a two graphs showing identical data. **A** uses a standard scale on the Y-axis. **B** uses a log scale on the Y-axis. In **A**, it is difficult to determine the value of the data points with values under 1000. In **B**, The value is clearly about 300.

## Creating Effective Graphs

Avoid 3-D charts. They clutter the image and distort the relative magnitude of the data. Be honest. If production was 0.15 in one and 0.17 in the other, don't start the graphs at 0.14 to make the difference look greater than it is. Test your graph by asking someone else to explain it.

Put related data on the same chart (Figure 8). Arrange the data so that the numbers that are most important to compare are in different series. If your main point is that nitrogen

production was higher around termite mounds, put the bars for the two termite mound distances next to each other. If your main point is that nitrogen production is higher in October, put the data from July next to the data from October. The data are the same, but the message is different.

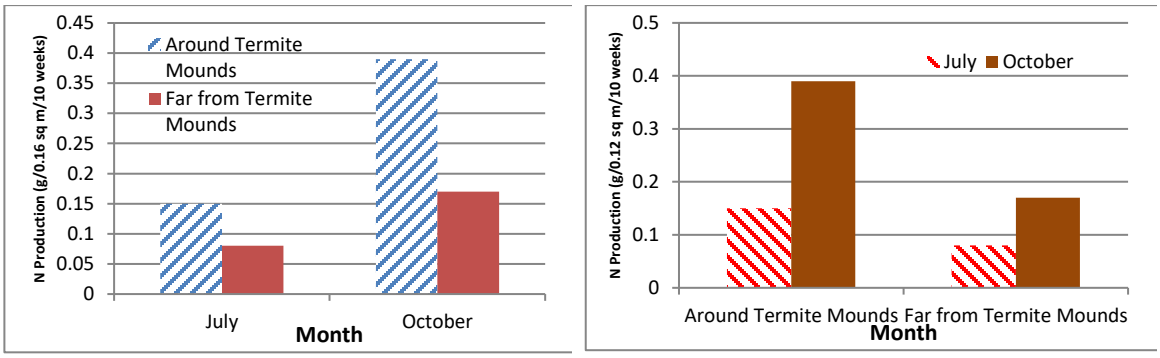



Figure 8. Comparison of two methods of graphing the same information. To direct your readers' attention, put the values to be compared in different series so that the bars are side by side. Data from: Fukuda, E., Macedo, M.C.M., Borges, M.J., & Pitaluga, G M. (2003). Effects of mounds of a termite Cornitermes cumulans on grass production and behavior of grazing cattle in semitropical grasslands in Brazil. *Grassland Science*, *49*, 24-25.

## Appendix E
## Using Scientific Citations and References

### Purpose

Citations and references serve two major functions: attributing credit for important ideas and allowing the reader to find the source of your information. Use a citation for any information that is not considered common knowledge. If you are quoting a source, put the quotation in quotation marks and follow it with a citation. Quotations are almost never used in scientific writing. Use your own words. Failure to properly use quotation marks and citations is plagiarism, a serious academic offence. Changing a few words does not fix plagiarism. Consult your instructor about any questions before submitting your work.

### Citation Format

A scientific citation must include the last name(s) of the author(s) and the year of publication. If the source is a book or a quote, add a page number. If there are two authors, list both. If there are three or more authors, list the first author and "et al." meaning "and others." The citation is part of the sentence; the period comes after it.

Examples of correct in-text citation form:

The hippocampus of mountain chickadees (*Poecile gambeli*) changes in response to juvenile food caching experience (Clayton, 2001).

Tregenza and Wedell (1997) found that male crickets (*Gryllus bimaculatus*) stopped responding to female calls when cuticular pheromones were removed.

### Reference Format

References provide all the information needed to find your sources. They are listed at the end of your paper, in alphabetical order. All authors are listed. Do not use *et al.*.The first line is not indented, but the other lines are. This is called "hanging indent." The following references are in APA (American Psychological Association) format. Your professor may require you to use a slightly different format.

If the article came from a journal, use this format:

Pepperberg, I. M., & Rosenberger, V. A. (2022). Delayed gratification: A grey parrot (Psittacus erithacus) will wait for more tokens. *Journal of Comparative Psychology*, *136*(1), 79.

If you retrieved the article through a database, the reference would look like this, containing a stable link or DOI:

Newsome, T. M., & Spencer, E. E. (2022). Megafires attract avian scavenging but carcasses still persist. *Diversity and Distributions*, *28*(3), 515–528. https://www.jstor.org/stable/48650472

For an article in a book that is a collection of articles, use this format:

Michener, G. R. (1984). Age, sex, and species differences in the annual cycles of ground-dwelling sciurids: Implications for sociality. In J.O. Murie and G. R. Michener (Eds.), *The biology of ground-dwelling squirrels* (pp. 81-107) Lincoln, NE: University of Nebraska Press.

Use this format for a book:

Wilson, E. O. (2002). *The future of life*. New York, NY: Vintage Books.

Your instructor may have minimum criteria for Internet sources. Use a regular citation and list it in the references like this:

National Interagency Fire Center (2023) Statistics. https://www.nifc.gov/fire-information/statistics

## Appendix F
## Writing Formal Reports

### Conventions

Writing should be clear, concise, and organized logically. Your goal is to explain, not confuse or impress. Write in the past tense. Most ecology journals use first person, active voice: "We hypothesized…" Use appropriate scientific vocabulary.

Time and Place

Describe a location by name and include the county and state. Report time on a 24-hour clock, where 8:00 a.m. is 0800 and 8:00 p.m. is 2000. Write the date so that the day and month cannot be confused. For example: "We collected the samples between 0700 and 1100 on 9 August 2023 from Lake Brimhall, Wasatch County, UT."

Metric Units

The metric system is the universal system of scientific measurement. Always use metric units in your writing. When converting units, be honest about the precision of your measurements. If you measured to the nearest inch, report your answer in whole centimeters.

Writing Numbers

Write whole numbers one through nine as text. Use numerals numbers of 10 or greater. Use scientific notation when writing very large or very small numbers. Exponents keep track of the number's magnitude. For example:

$10^4$ = 10,000 (a one followed by 4 zeros).
$10^{-4}$ = 0.0001 (a one that is four places to the right of the decimal).

Round off numbers to 3 or 4 significant digits. For example:

97,855,342 becomes $97.86 \times 10^6$.
0.00000078564 becomes $78.56 \times 10^{-8}$.

Use a leading zero; write 0.1 rather than .1. Avoid using a following zero; write 4 rather than 4.0. This decreases the probability of misreading the numbers.

Scientific Names

Standard scientific names are used internationally to avoid confusion. The scientific name of an organism includes both the genus and the species. It is always underlined or written in italics. The genus is always capitalized; the specific (or trivial) name never is. When you use the name of an organism, either use the scientific name consistently or use it the first time you use the common name.

- Killer whales (Orcinus orca) are becoming more common in this region.
- The cones of *Pinus contorta* are adapted to fire.

After you have used the scientific name once, you can use the common name or abbreviate the scientific name (*P. contorta*, or O. orca) as long as this won't cause any confusion. If you know the genus, but not the species, you can use "sp." to mean one unknown species or "spp." to mean two or more unknown species:

- The sample contained a large population of bacteria (Clostridium sp.).
- We found two kinds of sporozoans (*Plasmodium* spp.) in the mosquitoes.

**Organization**

Abstract
Report your findings in a brief summary. Include the purpose of the research, a very brief mention of methods, results, and conclusions. Abstracts usually contain fewer than 200 words. Follow this with a list of key words that would help a person index or search for your paper.

Introduction
State the background and purpose of your experiment. Discuss and cite other experiments on this topic. Why is this question or topic important? State your hypothesis and predictions.

Methods
Where and when did you collect the data? What instruments did you use? Include the manufacturer and model for any equipment. How many measurements did you take? What species were involved? It may be appropriate to cite a reference for a particular method. Figures may help the reader to understand your equipment or procedures. State what statistical tests and software you used. Another person should be able to replicate your experiment after reading your methods.

Results
Use sentences to state your main findings. Include summary statistics and computer-generated figures or tables. Refer to each table or graph in the text using the proper format: Levels of coliform bacteria were higher near the stream (Fig. 1). Each must have a caption that describes it. Captions go above tables and below figures. State the results of your statistical tests. If there was no significant difference, do not say that there was a difference. Your reader should be able to understand your results by looking at the figures and tables alone, or by reading the text alone.

Discussion
Explain the patterns you saw and relate your results to what is already known. Speculate on reasons for what you found, but do not state these ideas as facts. For example, say "The samples may have been more acidic because we collected them at night." Include appropriate literature citations. Note any changes you would make in repeating the experiment.

Literature Cited
List only works that you actually cited, not general references. Use the format in Appendix E. Put the references in alphabetical order using the last name of the first author for each. Use hanging indentation.

## Appendix G
## Creating and Presenting Scientific Posters

### General Considerations

Your audience will be viewing your poster from a meter or two away. Write your text with this in mind. Keep everything brief, simple and clear. Do not attempt to include all the material that you would include in a formal paper. Your viewers can ask you about the details. Your poster should be clear, uncluttered, and arranged to guide your audience through your work.

### Organization

Title
Decide on a clear, simple main message that reflects the contents of the poster. It may be a statement or a question. Put your name(s) under it. The font should be very large. If your poster will be presented to external audiences, put your institution's name on it.

Abstract
Use one sentence to say what you did (no details). Use one sentence to say what you found out. You can use another sentence for another major finding.

Introduction
Set context with a short paragraph explaining why you did your experiment. State the hypothesis you tested. Use one or two references to show what is already known or has already been done. Use proper citation format.

Methods
Briefly explain what you did. Mention specific equipment. You may wish to do this in a list of steps, but use past tense, not a list of directions. A figure may be helpful or photograph.

Results
Write a brief paragraph about what you found. Refer to your graphs in it.

Create one or more graphs to illustrate your main findings. Your message should be immediately obvious to your audience. Avoid tables, which provide more detail, but take longer to understand. Include a legend that tells the viewer what colors or patterns mean. Use specific labels such as "High Elevation" rather than the generic "Experimental."

Discussion and Conclusions
Explain what your data mean. Remember that while you can support or reject a hypothesis, you can't prove it. Mention anything a future researcher might want to do differently or point out a new avenue of research suggested by your work. You may have conclusions in bullet points.

References
List your references in appropriate format (See Appendix E).

Formatting the Poster

Make text and charts large. A photograph or other illustration can be informative. Use colors that increase readability. Arrange the elements in a logical order (Fig. F.1). If it won't all fit within the allowed space, omit illustrations (but not your main graphs) and make your text more concise. Your references can be in a relatively small font. Everything else should be readable from 2 m away when viewed at 100%.

If you will be printing the poster on a large-format printer, make sure that you have selected the correct poster size and margins. Carefully review the print preview to avoid expensive re-printing.

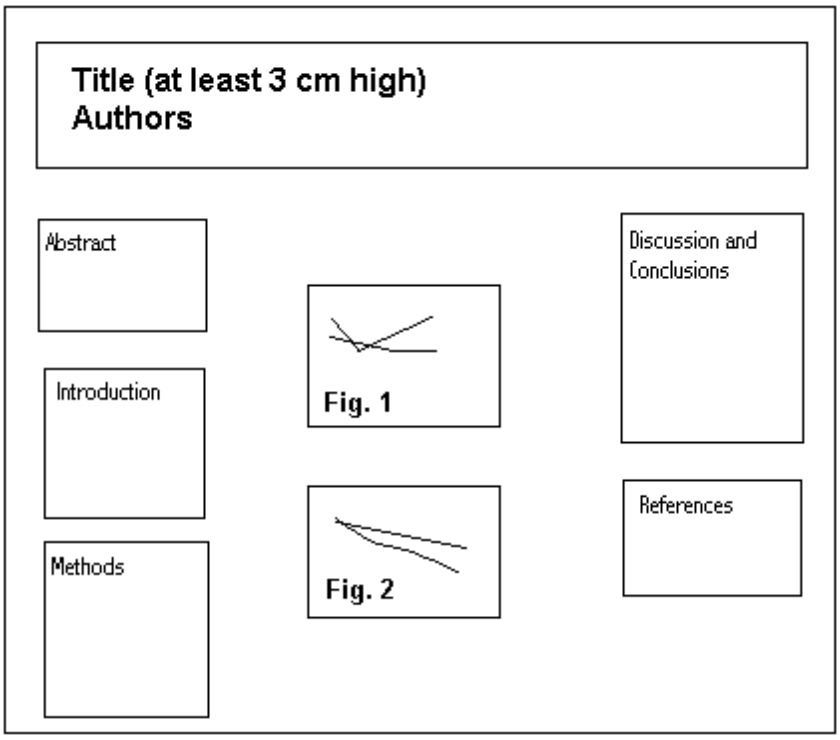



Figure 1. Sample of a poster layout.

**Presention**

Greet visitors to your poster. Be prepared to give a brief (1-2 minute) introduction to your research. Do not read or memorize this. Do not attempt to give a complete talk. Concentrate on the hypothesis, results, and conclusions. Be prepared to answer a variety of questions. Practice with a friend. You may want to work on your handshake. If you are presenting to an external audience, it is useful to have business cards available.

## Appendix G
## Giving Research Presentations

### General Conventions

Research presentation style and organization is similar to that used in technical papers (see Appendix F). Use metric units and scientific species names and write numbers in the correct format.

Scientific talks are generally accompanied by slides. Your media should add to your message, not overpower it. Avoid extraneous graphics (clip art) and gimmicks such as transition sounds and moving text. Carefully select your text and background colors to ensure that your slides can be read easily, even in poor lighting conditions. Make your text large (at least 18 pt.) and keep your sentences short. Bulleted lists and phrases are often preferable.

### Organization

Most presentations follow the same format as a paper, but with much less context in the introduction and fewer details in the methods.

Title: Use a title that gives a clear picture of the content of your presentation. On the title slide, list the name(s) of the author(s). For a talk to an external audience, list each author's affiliation, such as her department and institution. Do not repeat information if someone has just introduced you.

Abstract (optional): Report your findings in a brief summary or bullet point form. Some speakers omit the abstract in a presentation.

Introduction: State the theoretical background and purpose of your experiment. What is known about this topic? Why is this question or topic important? State your hypothesis and predictions. Slides defining terms or acronyms are helpful.

Methods: Methods slides may include photographs of subjects, habitats, and experimental setups. If your procedure was complex, a diagram or flow chart of methods is useful.

Results: Present your main findings. Take a moment to orient your audience to your graphs, describing the axes and providing a verbal legend. For example, "The solid bars represent the dark-exposed group and the open bars represent the light-exposed group." Note which results were significant and provide information such as sample size, summary statistics, and the results of statistical tests on the slides.

Discussion and Conclusions: Explain the patterns and relate your results to what is already known. Provide a concise statement of conclusions. Note any changes you would make in repeating the experiment. Identify possible directions for future research.

Literature Cited: For a course presentation, have a slide of key references. This is less common in presentations at professional meetings. Use a scientific format (see Appendix E). Don't read the slide; just briefly show it.

Acknowledgements (optional): Researchers commonly use their final slide to thank those who provided resources or other assistance. If it is not relevant, don't use it.

## Preparation

Most people are at least a little nervous about speaking in public, but the more often you present, the more confident you will become. You may never be completely calm about public speaking, but you can learn to manage your nervousness so that it energizes your presentation. Remember that you are the expert on your own research and that the audience is on your side. Preparation is the best antidote to nervousness. Make sure that you understand the criteria for the talk (purpose, required content, etc.), the time limits, and the available technology. Consider your audience and tailor your presentation to that specific group. Novice presenters tend to focus on themselves. Developing presenters tend to focus on their topic. Accomplished presenters focus on their audience.

Practice your presentation aloud, preferably in front of a friend who can give you useful feedback. Time your talk. **It is never acceptable to exceed the time limit**, so decide what you will omit if your talk is running long. Practice without notes.

Start preparing your media well in advance so that you have time to recover from problems with technology. Have copies of your presentation in different forms (e.g., upload it and have a jump drive). Be prepared to present even if your technology fails.

## Speaking

Position yourself so that everyone can see the media. Speak loudly, clearly, and to the audience. Do not memorize your talk and do not read the slides to the audience. Instead, speak in a conversational style, facing the audience. Use simple, active words and avoid slang, jargon, and filler words such as "like" and "um." Avoid ending your sentences on a rising note that makes statements sound like questions. Keep track of your time.

Finish your presentation with a statement such as, "Thank you" or "I'd be happy to take your questions," so the audience knows you are done. Do not just trail off or shrug your shoulders and say, "That's all I have."

## Taking Questions

Listen carefully to what is asked and repeat the question before answering so that the audience can hear it. Stick to the point and make sure you have answered the question completely but succinctly. If you do not know the answer, stay calm and be honest about what you do and do not know. You may have additional data or analyses that did not fit into the time limit. Put this material on slides after your final slide in case it will help you to answer a relevant question. End the question session by saying, "Thank you."