2 Principles of Science and Systems

▲Student interns measure plant growth in experimental plots in the B4Warmed study in northern Minnesota.

Learning Outcomes

After studying this chapter, you should be able to:

2.1 Describe the scientific method and explain how it works.

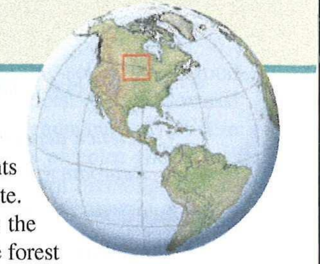
2.2 Explain systems and how they're useful in science.

2.3 Evaluate the role of scientific consensus and conflict.

"The ultimate test of a moral society is the kind of world that it leaves to its children."

— Dietrich Bonhoeffer

CASE STUDY



Forest Responses to Global Warming

How will forests respond to climate change? This is one of the great unknowns in environmental science today. Will northern regions that now support boreal forest shift to another biome—hardwood forest, open savannah, grassland, or something entirely different? With rising emissions of CO_2 and other greenhouse gases, climate models predict that boreal forests will move north by about 480 km (300 mi) within this century. But there's a great deal of uncertainty in this prediction.

How do environmental scientists approach and analyze such complex questions? One strategy is to grow plants in a greenhouse, and test plant responses to different temperature and moisture levels. By changing just one variable at a time, we can get an approximation of responses to environmental change. But this approach misses the complex species interactions that influence plant growth in a real ecosystem, so an alternative approach is to use field tests in which mixtures of plants are grown in natural settings that include competition for resources, predator/prey interactions, natural climatic variations, and other ecological factors.

Professor Peter Reich and his colleagues and student research assistants are now carrying out such a field study in a patch of boreal (northern) forest in Minnesota. Calling this experiment B4Warmed, which stands for Boreal Forest Warming at an Ecotone in Danger, they are artificially raising ambient temperatures in a series of boreal forest plots, to emulate warming climate conditions.

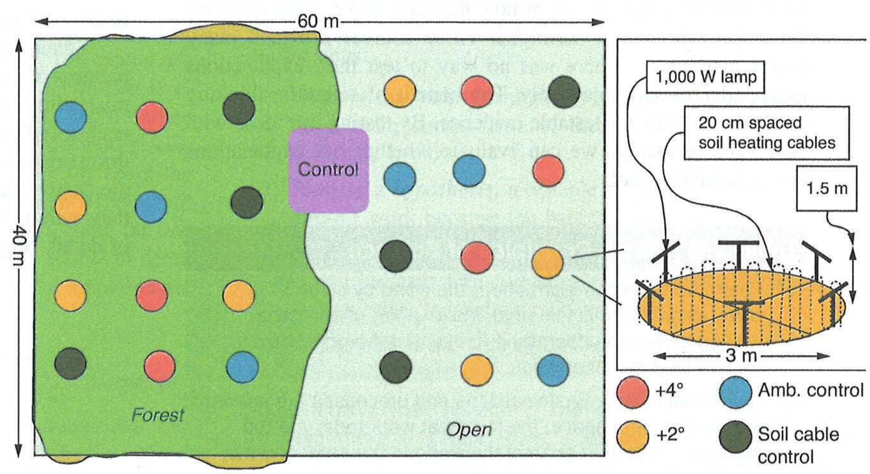


FIGURE 2.1 Experimental design for B4Warmed Study.

The group established 96 circular experimental plots, each 3 meters (9.8 ft) in diameter (fig. 2.1). Each plot was planted with a mixture of tree species and annual understory plants. The plots were then randomly assigned to one of four treatments. Half the plots are in mature forest, and half are in forest openings. Half are kept 2°C above ambient temperatures, and half are kept 4°C higher than ambient temperatures, using infrared lamps placed around the plots, as well as buried heat cables (fig. 2.2). Control plots (with no temperature manipulations) are also maintained for comparison with treatments.

It's too early to know exactly what the long-term effects of warming will be on the northern forest community. It seems likely that species such as aspen, spruce, and birch, which are now at the southern edge of their range in the study area, won't do as well under a warmer climate as the temperate maple-oak forests now growing further south. However, both northern and temperate species may perform poorly under warmer conditions. If so, neither our current forest trees nor their potential replacements may be well suited to our future climate. This experiment will enable us to assess the potential for climate change to alter future forest composition.

One preliminary result from this study that appears to offer good news is that the CO_2 emissions both from forest plants and from the soil are lower than expected at higher temperatures. Apparently both standing vegetation and soil microbes alter their metabolic rates to acclimate to ambient environmental conditions. Thus the feedback cycles predicted to exacerbate global warming effects may not be as bad as we feared.

This kind of careful, rational, systematic research is the hallmark of modern science. It has given us powerful insights into how our world works. In this chapter, we'll look at how scientists form and answer other questions about our environment.

FIGURE 2.2 A student researcher adjusts the electrical panel that controls heat lamps and heating cables.

2.1 What Is Science?

- *Science depends on careful, objective, logical analysis.*
- *Reproducible results are essential in science.*
- *Science depends on orderly testing of hypotheses.*

Science is a process for producing knowledge methodically and logically. Derived from *scire,* "to know" in Latin, science depends on making precise observations of natural phenomena. We develop or test theories (proposed explanations of how a process works) using these observations. "Science" also refers to the cumulative body of knowledge produced by many scientists. Science is valuable because it helps us understand the world and meet practical needs, such as new medicines, new energy sources, or new foods.

Science rests on the assumption that the world is knowable and that we can learn about the world by careful observation (table 2.1). For early philosophers of science, this assumption was a radical departure from religious and philosophical approaches. In the Middle Ages, the ultimate sources of knowledge about how crops grow, how diseases spread, or how the stars move, were religious authorities or cultural traditions. These sources provided many useful insights, but there was no way to test their explanations independently and objectively. The benefit of scientific thinking is that it searches for testable evidence. By testing our ideas with observable evidence, we can evaluate whether our explanations are reasonable or not.

Table 2.1 Basic Principles of Science
1. *Empiricism:* We can learn about the world by careful observation of empirical (real, observable) phenomena; we can expect to understand fundamental processes and natural laws by observation.
2. *Uniformitarianism:* Basic patterns and processes are uniform across time and space; the forces at work today are the same as those that shaped the world in the past, and they will continue to do so in the future.
3. *Parsimony:* When two plausible explanations are reasonable, the simpler (more parsimonious) one is preferable. This rule is also known as Ockham's razor, after the English philosopher who proposed it.
4. *Uncertainty:* Knowledge changes as new evidence appears, and explanations (theories) change with new evidence. Theories based on current evidence should be tested on additional evidence, with the understanding that new data may disprove the best theories.
5. *Repeatability:* Tests and experiments should be repeatable; if the same results cannot be reproduced, then the conclusions are probably incorrect.
6. *Proof is elusive:* We rarely expect science to provide absolute proof that a theory is correct, because new evidence may always undermine our current understanding.
7. *Testable questions:* To find out whether a theory is correct, it must be tested; we formulate testable statements (hypotheses) to test theories.

Science depends on skepticism and accuracy

Ideally, scientists are skeptical. They are cautious about accepting proposed explanations until there is substantial evidence to support them. Even then, as we saw in the case study about global warming that opened this chapter, explanations are considered only provisionally true, because there is always a possibility that some additional evidence may appear to disprove them. Scientists also aim to be methodical and unbiased. Because bias and methodical errors are hard to avoid, scientific tests are subject to review by informed peers, who can evaluate results and conclusions (fig. 2.3). The peer review process is an essential part of ensuring that scientists maintain good standards in study design, data collection, and interpretation of results.

Scientists demand **reproducibility** because they are cautious about accepting conclusions. Making an observation or obtaining a result just once doesn't count for much. You have to produce the same result consistently to be sure that your first outcome wasn't a fluke. Even more important, you must be able to describe the conditions of your study so that someone else can reproduce your findings. Repeating studies or tests is known as **replication.**

Science also relies on accuracy and precision. Accuracy is correctness of measurements. Inaccurate data can produce sloppy and misleading conclusions (fig. 2.4). Precision means repeatability of results and level of detail. The classic analogy for repeatability is throwing darts at a dart board. You might throw ten darts and miss the center every time, but if all the darts hit nearly the same spot, they were very precise. Another way to think of precision is levels of detail. Suppose you want to measure how much snow fell last

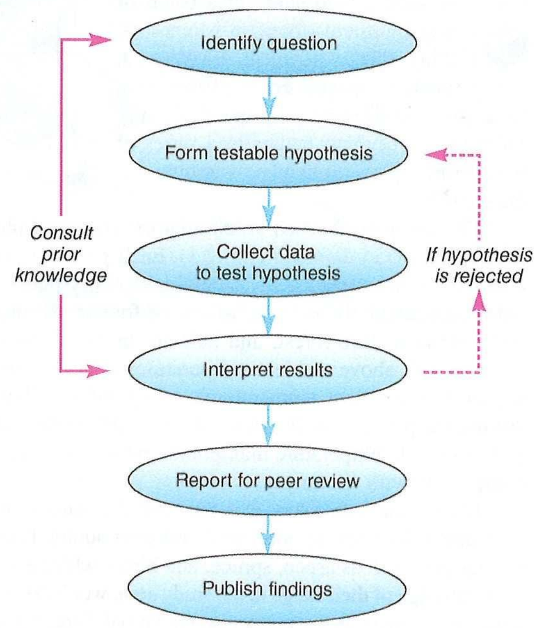


FIGURE 2.3 Ideally, scientific investigation follows a series of logical, orderly steps to formulate and test hypotheses.

FIGURE 2.4 Making careful, accurate measurements and keeping good records are essential in scientific research.

night, so you take out your ruler, which is marked in centimeters, and you find that the snow is just over 6 cm deep. You cannot tell if it is 6.3 cm or 6.4 cm because the ruler doesn't report that level of detail. If you average several measurements, you might find an average depth of 6.4333 cm. If you report all four decimal places, it will imply that you know more than you really do about the snow depth. If you had a ruler marked in millimeters (one-tenth of a centimeter), you could find a depth of 6.4 cm. Here, the one decimal place would be a **significant number,** or a level of detail you actually knew. Reporting 6.4333 cm would be inappropriate because the last three digits are not meaningful.

Deductive and inductive reasoning are both useful

Ideally, scientists deduce conclusions from general laws that they know to be true. For example, if we know that massive objects attract each other (because of gravity), then it follows that an apple will fall to the ground when it releases from the tree. This logical reasoning from general to specific is known as **deductive reasoning.** Often, however, we do not know general laws that guide natural systems. We observe, for example, that birds appear and disappear as a year goes by. Through many repeated observations in different places, we can infer that the birds move from place to place. We can develop a general rule that birds migrate seasonally. Reasoning from many observations to produce a general rule is **inductive reasoning.** Although deductive reasoning is more logically sound than inductive reasoning, it only works when our general laws are correct. We often rely on inductive reasoning to understand the world, because we have few immutable laws.

Sometimes it is insight, as much as reasoning, that leads us to an answer. Many people fail to recognize the role that insight, creativity, aesthetics, and luck play in research. Some of our most important discoveries were made not because of superior scientific method and objective detachment, but because the investigators were passionately interested in their topics and pursued hunches that appeared unreasonable to fellow scientists. A good example is Barbara McClintock, the geneticist who discovered that genes in corn can move and recombine spontaneously. Where other corn geneticists saw random patterns of color and kernel size, McClintock's years of experience in corn breeding, and an uncanny ability to recognize patterns, led her to guess that genes could recombine in ways that no one had yet imagined. Her intuitive understanding led to a theory that took other investigators years to accept.

Testable hypotheses and theories are essential tools

Science also depends on orderly testing of hypotheses, a process known as the scientific method. You may already be using the scientific method without being aware of it. Suppose you have a flashlight that doesn't work. The flashlight has several components (switch, bulb, batteries) that could be faulty. If you change all the components at once, your flashlight might work, but a more methodical series of tests will tell you more about what was wrong with the system—knowledge that may be useful the next time you have a faulty flashlight. So you decide to follow the standard scientific steps:

1. *Observe* that your flashlight doesn't light; also, that there are three main components of the lighting system (batteries, bulb, and switch).
2. Propose a ***hypothesis,*** a testable explanation: "The flashlight doesn't work because the batteries are dead."
3. Develop a *test* of the hypothesis and *predict* the result that would indicate your hypothesis was correct: "I will replace the batteries; the light should then turn on."
4. Gather *data* from your test: After you replaced the batteries, did the light turn on?
5. *Interpret* your results: If the light works now, then your hypothesis was right; if not, then you should formulate a new hypothesis, perhaps that the bulb is faulty, and develop a new test for that hypothesis.

In systems more complex than a flashlight, it is almost always easier to prove a hypothesis wrong than to prove it unquestionably true. This is because we usually test our hypotheses with observations, but there is no way to make every possible observation. The philosopher Ludwig Wittgenstein illustrated this problem as follows: Suppose you saw hundreds of swans, and all were white. These observations might lead you to hypothesize that all swans were white. You could test your hypothesis by viewing thousands of swans, and each observation might support your hypothesis, but you could never be entirely sure that it was correct. On the other hand, if you saw just one black swan, you would know with certainty that your hypothesis was wrong.

As you'll read in later chapters, the elusiveness of absolute proof is a persistent problem in environmental policy and law. You can never absolutely prove that the toxic waste dump up the street is making you sick. The elusiveness of proof often decides environmental liability lawsuits.

When an explanation has been supported by a large number of tests, and when a majority of experts have reached a general consensus that it is a reliable description or explanation, we call it a **scientific theory.** Note that scientists' use of this term is very different from the way the public uses it. To many people, a theory is speculative and unsupported by facts. To a scientist, it means just the opposite: While all explanations are tentative and open to revision and correction, an explanation that counts as a scientific theory is supported by an overwhelming body of data and experience, and it is generally accepted by the scientific community, at least for the present (fig. 2.5).

Understanding probability helps reduce uncertainty

One strategy to improve confidence in the face of uncertainty is to focus on probability. Probability is a measure of how likely something is to occur. Usually, probability estimates are based on a set of previous observations or on standard statistical measures. Probability does not tell you what *will* happen, but it tells you what *is likely* to happen. If you hear on the news that you have a 20 percent chance of catching a cold this winter, that means that 20 of every 100 people are likely to catch a cold. This doesn't mean that you will catch one. In fact, it's more likely that you won't catch a cold than that you will. If you hear that 80 out of every 100 people will catch a cold, you still don't know whether you'll get sick, but there's a much higher chance that you will.

Science often involves probability, so it is important to be familiar with the idea. Sometimes probability has to do with random chance: If you flip a coin, you have a random chance of getting heads or tails. Every time you flip, you have the same 50 percent probability of getting heads. The chance of getting ten heads in a row is small (in fact, the chance is 1 in 210, or 1 in 1,024), but on any individual flip you have exactly the same 50 percent chance, since this is a random test.

FIGURE 2.5 Data collection and repeatable tests support scientific theories. Here students use telemetry to monitor radio-tagged fish.

Sometimes probability is weighted by circumstances: Suppose that about 10 percent of the students in this class earn an A each semester. Your likelihood of being in that 10 percent depends a great deal on how much time you spend studying, how many questions you ask in class, and other factors. Sometimes there is a combination of chance and circumstances: The probability that you will catch a cold this winter depends partly on whether you encounter someone who is sick (largely random chance) and whether you take steps to stay healthy (get enough rest, wash your hands frequently, eat a healthy diet, and so on).

Scientists often increase their confidence in a study by comparing results to a random sample or a larger group. Suppose that 40 percent of the students in your class caught a cold last winter. This *seems* like a lot of colds, but is it? One way to decide is to compare to the cold rate in a larger group. You call your state epidemiologist, who took a random sample of the state population last year: She collected 200 names from the telephone book and called each to find out if each got a cold last year. A larger sample, say 2,000 people, would have been more likely to represent the actual statewide cold rate. But a sample of 200 is much better than a sample of 50 or 100. The epidemiologist tells you that in your state as a whole, only 20 percent of people caught a cold.

Now you know that the rate in your class (40 percent) was quite high, and you can investigate possible causes for the difference. Perhaps people in your class got sick because they were short on sleep, because they tended to stay up late studying. You could test whether studying late was a contributing factor by comparing the frequency of colds in two groups: those who study long and late, and those who don't. Suppose it turns out that among the 40 late-night studiers, 30 got colds (a rate of 75 percent). Among the 60 casual studiers, only 10 got colds (17 percent). This difference would give you a good deal of confidence that staying up late contributes to getting sick. (Note, however, that all 40 of the studying group got good grades!)

Statistics can indicate the probability that your results were random

Statistics can help in experimental design as well as in interpreting data (see Exploring Science, pp. 42–43). Many statistical tests focus on calculating the probability that observed results could have occurred by chance. Often, the degree of confidence we can assign to results depends on sample size as well as the amount of variability between groups.

Ecological tests are often considered significant if there is less than 5 percent probability that the results were achieved by random chance. A probability of less than 1 percent gives still greater confidence in the results.

As you read this book, you will encounter many statistics, including many measures of probability. When you see these numbers, stop and think: Is the probability high enough to worry about? How high is it compared to other risks or chances you've read about? What are the conditions that make probability higher or lower? Science involves many other aspects of statistics.

Experimental design can reduce bias

The study of colds and sleep deprivation is an example of an observational experiment, one in which you observe natural events and interpret a causal relationship between the variables. This kind of study is also called a **natural experiment,** one that involves observation of events that have already happened. Many scientists depend on natural experiments: A geologist, for instance, might want to study mountain building, or an ecologist might want to learn about how species coevolve, but neither scientist can spend millions of years watching the process happen. Similarly, a toxicologist cannot give people a disease just to see how lethal it is.

Other scientists can use **manipulative experiments,** such as the B4Warmed experiment in the opening case study for this chapter, in which some conditions are deliberately altered and all other variables are held constant (fig. 2.6). In one famous manipulative study, ecologists Edward O. Wilson and Robert MacArthur were interested in how quickly species colonize small islands, depending on distance to the mainland. They fumigated several tiny islands in the Florida Keys, killing all resident insects, spiders, and other invertebrates. They then monitored the islands to learn how quickly ants and spiders recolonized them from the mainland or other islands.

Most manipulative experiments are done in the laboratory, where conditions can be carefully controlled. Suppose you are interested in studying whether lawn chemicals contribute to deformities in tadpoles. You might keep two groups of tadpoles in fish tanks and expose one to chemicals. In the lab, you could ensure that both tanks had identical temperatures, light, food, and oxygen. By comparing a treatment (exposed) group and a control (unexposed) group, you have also made this a **controlled study.**

Often there is a risk of experimenter bias. Suppose the researcher sees a tadpole with a small nub that looks like it might become an extra leg. Whether she calls this nub a deformity might depend on whether she knows that the tadpole is in the treatment

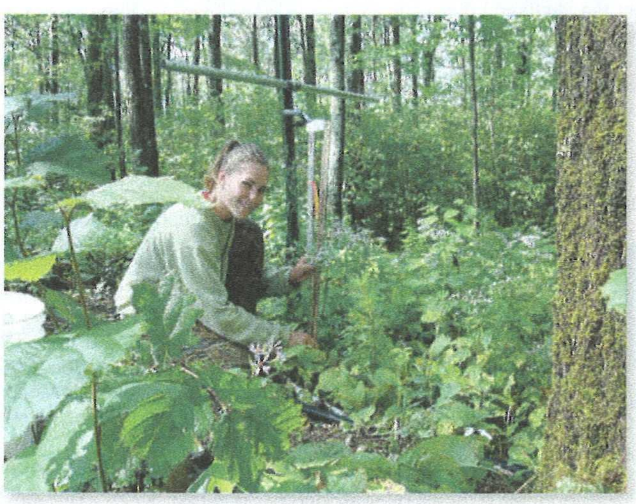


FIGURE 2.6 A researcher gathers data from the B4Warmed field experiment in the boreal forest.

FIGURE 2.7 A model uses just the essential elements to represent a complex system.

group or the control group. To avoid this bias, **blind experiments** are often used, in which the researcher doesn't know which group is treated until after the data have been analyzed. In health studies, such as tests of new drugs, **double-blind experiments** are used, in which neither the subject (who receives a drug or a placebo) nor the researcher knows who is in the treatment group and who is in the control group.

In each of these studies there is one **dependent variable** and one, or perhaps more, **independent variables.** The dependent variable, also known as a response variable, is affected by the independent variables. In a graph, the dependent variable is on the vertical (Y) axis, by convention. Independent variables are rarely really independent (they are affected by the same environmental conditions as the dependent variable, for example). Many people prefer to call them explanatory variables, because we hope they will explain differences in the dependent variable.

Models are an important experimental strategy

Another way to gather information about environmental systems is to use **models.** A model is a simple representation of something. Perhaps you have built a model airplane. The model doesn't have all the elements of a real airplane, but it has the most important ones for your needs. A simple wood or plastic airplane has the proper shape, enough to allow a child to imagine it is flying (fig. 2.7). A more complicated model airplane might have a small gas engine, just enough to let a teenager fly it around for short distances.

Similarly, scientific models vary greatly in complexity, depending on their purposes. Some models are physical models: Engineers test new cars and airplanes in wind tunnels to see how they perform, and biologists often test theories about evolution and genetics using "model organisms" such as fruit flies or rats as a surrogate for humans.

Most models are numeric, though. A model could be a mathematical equation, such as a simple population growth model ($N_t = rN_{(t-1)}$). Here the essential components are number (N) of individuals at time t (N_t), and the model proposes that N_t is equal to the growth rate (r) times the number in the previous time period ($N_{(t-1)}$). This model is a very simplistic representation of population change, but it is useful because it precisely describes a relationship between population size and growth rate. Also, by converting the symbols to numbers, we can predict populations over time. For example, if last year's rabbit population was 100, and the growth rate is 1.6 per year, then this year's population will

EXPLORING SCIENCE

Why Do Scientists Answer Questions with a Number?

Statistics are numbers that let you evaluate and compare things. "Statistics" is also a field of study that has developed meaningful methods of comparing those numbers. By both definitions, statistics are widely used in environmental sciences, partly because they can give us a useful way to assess patterns in a large population, and partly because the numbers can give us a measure of confidence in our research or observations. Understanding the details of statistical tests can take years of study, but a few basic ideas will give you a good start toward interpreting statistics.

1. **Descriptive statistics help you assess the general state of a group.** In many towns and cities, the air contains dust, or particulate matter, as well as other pollutants. From personal experience you might know your air isn't as clean as you'd like, but you may not know how clean or dirty it is. You could start by collecting daily particulate measurements to find average levels. An averaged value is more useful than a single day's values, because daily values may vary a great deal, but general, long-term conditions affect your general health. Collect a sample every day for a year; then divide the sum by the number of days, to get a **mean** (average) dust level. Suppose you found a mean particulate level of 30 micrograms per cubic meter ($\mu g/m^3$) of air. Is this level high or low? In 1997 the EPA set a standard of 50 $\mu g/m^3$ as a limit for allowable levels of coarse particulates (2.5–10 micrometers in diameter). Higher levels tend to be associated with elevated rates of asthma and other respiratory diseases. Now you know that your town, with an annual average of 30 $\mu g/m^3$, has relatively safe air, after all.

2. **Statistical samples.** Although your town is clean by EPA standards, how does it compare with the rest of the cities in the country? Testing the air in *every* city is probably not possible. You could compare your town's air quality with a **sample**, or subset of cities, however. A large, random sample of cities should represent the general "population" of cities reasonably well. Taking a large sample reduces the effects of outliers (unusually high or low values) that might be included. A random sample minimizes the chance that you're getting only the worst sites, or only a collection of sites that are close together, which might all have similar conditions. Suppose you get average annual particulate levels from a sample of 50 randomly selected cities. You can draw a frequency distribution, or histogram, to display your results (fig. 1). The mean value of this group is 36.8 $\mu g/m^3$, so by comparison your town (at 30 $\mu g/m^3$) is relatively clean.

Many statistical tests assume that the sample has a normal, or Gaussian, frequency distribution, often described as a bell-shaped curve (fig. 2). In this distribution, the mean is near the center of the range of values, and most values are fairly close to the mean. Large and random samples are more likely to fit this shape than are small and nonrandom samples.

3. **Confidence.** How do you know that the 50 cities you sampled really represent all the cities in the country? You can't ever be completely certain, but you can use estimates, such as confidence limits, to express the reliability of your mean statistic. Depending on the size of your sample (not 10, not 500, but 50) and the amount of variability in the sample data, you can calculate a confidence interval that the mean represents the whole population (all cities). Confidence levels, or confidence intervals, represent the likelihood that your statistics correctly represent the entire population. For the mean of your sample, a confidence interval tells you the probability that your sample is similar to other random samples of the population. A common convention is to compare values with a 95 percent confidence level, or a probability of 5 percent or less that your conclusions are misleading. Using statistical software, we can calculate that, for our 50 cities, the mean is 36.8 $\mu g/m^3$, and the confidence interval is 35.0 to 38.6. This suggests that, if you take 1,000 samples from the entire population of cities, 95 percent of those samples ought to be within 2 $\mu g/m^3$ of your mean. This indicates that your mean is reliable and representative.

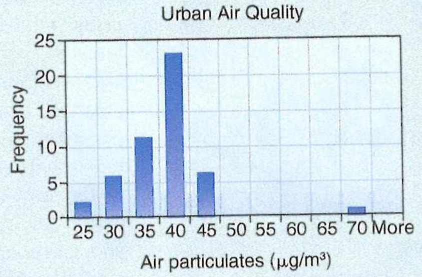


FIGURE 1 Average annual airborne dust levels for 50 cities.

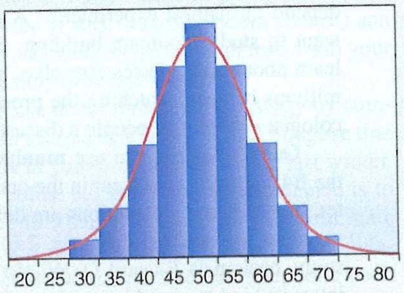


FIGURE 2 A normal distribution.

4. **Is your group unusual?** Once you have described your group of cities, you can compare it with other groups. For example, you might believe that Canadian cities have cleaner air than U.S. cities. You can compare mean air quality levels for the two groups. Then you can calculate confidence intervals for the difference between the means, to see if the difference is meaningful.

5. **Evaluating relationships between variables.** Are respiratory diseases correlated with air pollution? For each city in your sample, you could graph pollution and asthma rates (fig. 3). If the graph looks like a loose cloud of dots, there is no clear relationship. A tight, linear pattern of dots trending upward to the right indicates a strong and positive relationship. You can also use a statistical package to calculate an equation to describe the relationship and, again, confidence intervals for the equation. This is known as a regression equation.

6. **Lies, damned lies, and statistics.** Can you trust a number to represent a complex or large phenomenon? One of the devilish

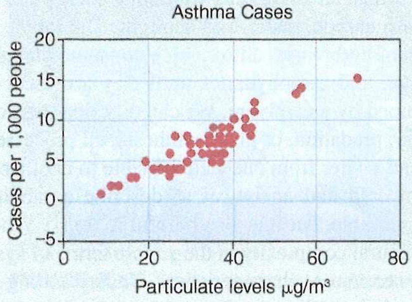


FIGURE 3 A dot plot shows relationships between variables.

details of representing the world with numbers is that those numbers can be tabulated in many ways. If we want to assess the greatest change in air quality statistics, do we report rates of change or the total amount of change? Do we look at change over five years? 25 years? Do we accept numbers selected by the EPA, by the cities themselves, by industries, or by environmental groups? Do we trust that all the data were collected with a level of accuracy and precision that we would accept if we knew the hidden details in the data-gathering process? Like all information, statistics need to be interpreted in terms of who produced them, when, and why. Awareness of some of the standard assumptions behind statistics, such as sampling, confidence, and probability, will help you interpret statistics that you see and hear.

Test your comprehension

1. What is a mean? How would you use one?
2. What is a Gaussian or normal distribution? What shape does it create in a graph?
3. What do statisticians mean by confidence limits?

be 160. Next year's population will be 160 × 1.6, or 256. This is a simple model, then, but it can be useful. A more complicated model might account for deaths, immigration, emigration, and other factors.

More complicated mathematical models can be used to describe and calculate more complex processes, such as climate change (fig. 2.8) or economic growth. These models are also useful because they allow the researcher to manipulate variables without actually destroying anything. An economist can experiment with different interest rates to see how they affect economic growth. A climatologist can raise the variables for CO_2 levels and see how quickly the variables for temperatures respond. These models are often called simulation models, because they simulate a complex system. Of course, the results depend on the assumptions built into the models. One model might show temperature rising quickly in response to CO_2; another might show temperature rising more slowly, depending on how evaporation, cloud cover, and other variables are taken into account. Consequently, simulations can produce powerful but controversial results. If multiple models generally agree, though, as in the cases of climate models that agree on generally upward temperature trends, we can have confidence that the overall predictions are reliable. These models are also very useful in laying out and testing our ideas about how a system works.

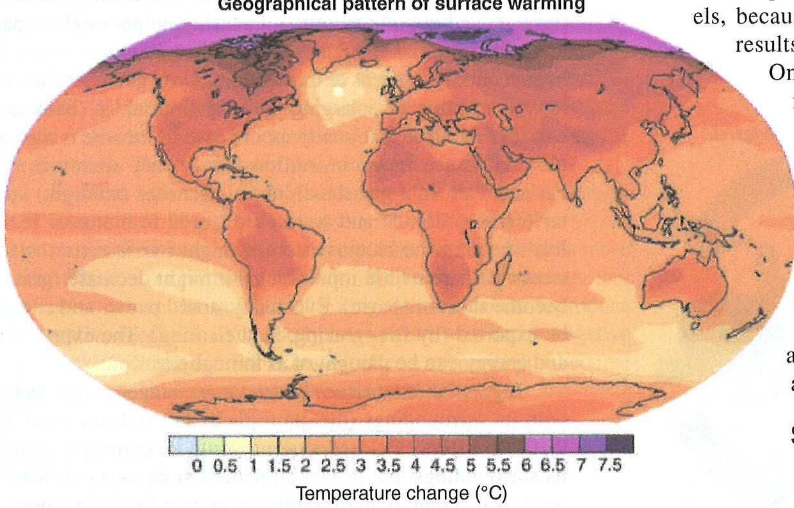


FIGURE 2.8 Numerical models, calculated from observed data, can project future scenarios. Here, temperature changes in 2090–2099 are modeled, relative to 1980–1999 temperatures.

Source: *IPCC Fourth Assessment Report 2007, model scenario AIB SRES.*

Section Review

1. What is science? What are some of its basic principles?
2. Why are widely accepted, well-defended scientific explanations called "theories"?
3. Draw a diagram showing the steps of the scientific method, and explain why each is important.

2.2 Systems Involve Interactions

- *A system is a network of interdependent components and processes that together have properties beyond those of individual parts.*
- *Feedbacks are self-regulating mechanisms in which the results of a process affect the process itself.*
- *Homeostasis (the ability to maintain stability) and resilience (the ability to recover from disturbance) are important characteristics of systems.*

The forest ecosystem you examined in the opening case study of this chapter is interesting because it is composed of many interdependent parts. By studying those parts, we can understand how similar ecosystems might function, and why. The idea of **systems,** including ecosystems, is central in environmental science. A system is a network of interdependent components and processes, with materials and energy flowing from one component of the system to another. For example, "ecosystem" is probably a familiar term for you. This simple word stands for a complex assemblage of animals, plants, and their environment, through which materials and energy move.

The idea of systems is useful because it helps us organize our thoughts about the inconceivably complex phenomena around us. For example, an ecosystem might consist of countless animals and plants and their physical surroundings. (You yourself are a system consisting of millions of cells, complex organs, and innumerable bits of energy and matter that move through you.) Keeping track of all the elements and their relationships in an ecosystem would probably be an impossible task. But if we step back and think about them in terms of plants, herbivores, carnivores, and decomposers, then we can start to comprehend how it works (fig. 2.9).

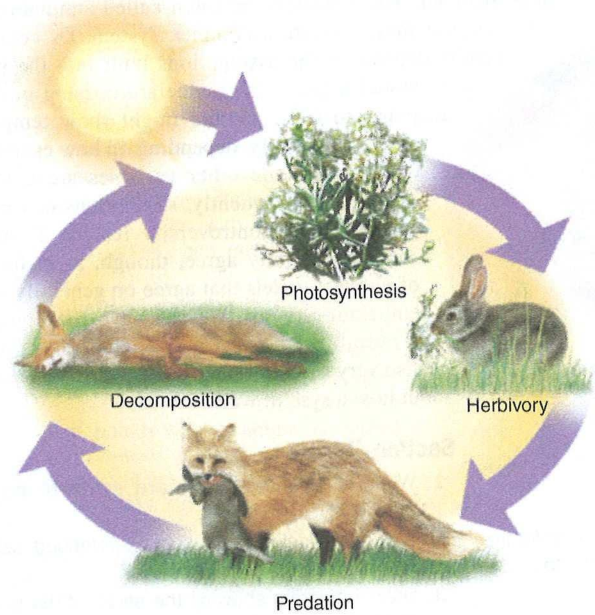


FIGURE 2.9 A system can be described in very simple terms.

We can use some general terms to describe the components of a system. A simple system consists of state variables (also called compartments), which store resources such as energy, matter, or water; and flows, or the pathways by which those resources move from one state variable to another. In figure 2.9, the plant and animals represent state variables. The plant represents many different plant types, all of which are things that store solar energy and create carbohydrates from carbon, water, and sunlight. The rabbit represents many kinds of herbivores, all of which consume plants, then store energy, water, and carbohydrates until they are used, transformed, or consumed by a carnivore. We can describe the flows in terms of herbivory, predation, or photosynthesis, all processes that transfer energy and matter from one state variable to another.

It may seem cold and analytical to describe a rabbit or a flower as a state variable, but it is also helpful to do so. When we start discussing natural complexity in the simple terms of systems, we can identify common characteristics. Understanding these characteristics can help us diagnose disturbances or changes in the system: for example, if rabbits become too numerous, herbivory can become too rapid for plants to sustain. Overgrazing can lead to widespread collapse of this system. Let's examine some of the common characteristics we can find in systems.

Systems can be described in terms of their characteristics

Open systems are those that receive inputs from their surroundings and produce outputs that leave the system. Almost all natural systems are open systems. In principle, a **closed system** exchanges no energy or matter with its surroundings, but these are rare. Often we think of pseudo-closed systems, those that exchange only a little energy but no matter with their surroundings. **Throughput** is a term we can use to describe the energy and matter that flow into, through, and out of a system. Larger throughput might expand the size of state variables. For example, you can consider your household economy in terms of throughput. If you get more income, you have the option of enlarging your state variables (bank account, car, television, . . .). Usually an increase in income is also associated with an increase in outflow (the money spent on that new car and TV). In a grassland, inputs of energy (sunlight) and matter (carbon dioxide and water) are stored in biomass. If there is lots of water, the biomass storage might increase (in the form of trees). If there's little input, biomass might decrease (grass could become short or sparse). Eventually stored matter and energy may be exported (by fire, grazing, land clearing). The exported matter and energy can be thought of as throughput.

A grassland is an *open system:* it exchanges matter and energy with its surroundings (the atmosphere and soil, for example; fig. 2.10). In theory, a closed system would be entirely isolated from its surroundings, but in fact all natural systems are at least partly open. A fish tank is an example of a system that is less open than a grassland, because it can exist with only sunlight and carbon dioxide inputs (fig. 2.11).

Systems also experience positive and negative feedback mechanisms. A **positive feedback** is a self-perpetuating process.

FIGURE 2.10 Environmental scientists often study open systems. Here students at Cedar Creek study the climate-vegetation system, gathering plant samples that grew in carbon dioxide-enriched air pumped from the white poles, but other factors (soil, moisture, sunshine, temperature) are not controlled.

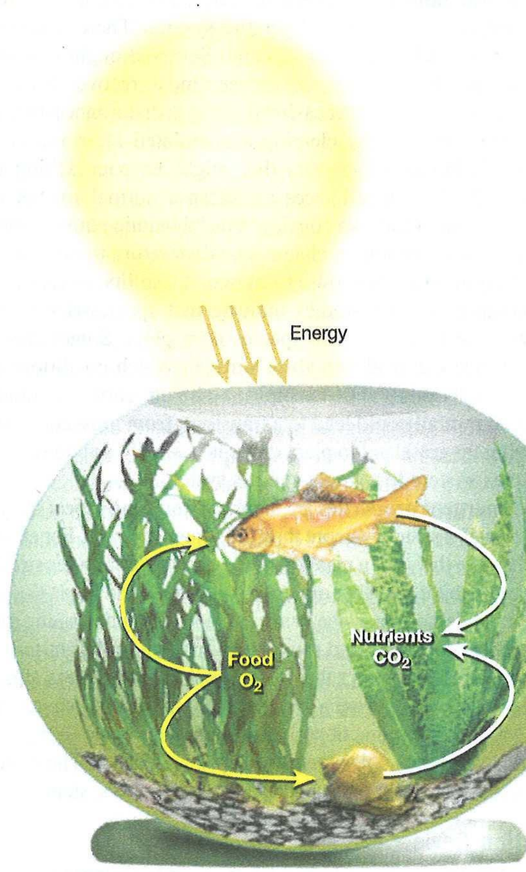
In a grassland, a grass plant grows new leaves, and the more leaves it has, the more energy it can capture for producing more leaves. In other words, in a positive feedback mechanism, increases in a state variable (biomass) lead to further increases in that state variable (more biomass). In contrast, a **negative feedback** is a process that suppresses change. If grass grows very rapidly, it may produce more leaves than can be supported by available soil moisture. With insufficient moisture, the plant begins to die back.

In climate systems (chapter 15) positive and negative feedbacks are important ideas. For example, as warm summers melt ice in the Arctic, newly exposed water surfaces absorb heat, which leads to further melting, which leads to further heat absorption . . . This is positive feedback. In contrast, clouds can have a negative feedback effect (although there are debates on the net effect of clouds). A warming atmosphere can evaporate more water, producing clouds. Clouds block some solar heat, which reduces the evaporation. Thus clouds can slow the warming process.

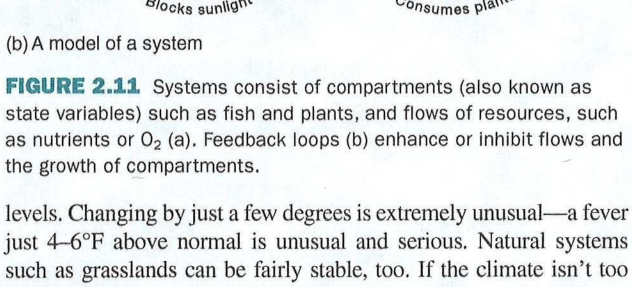
Positive and negative feedback mechanisms are also important in understanding population dynamics (chapter 6). For example, more individuals produce more young, which produces more individuals . . . (a positive feedback). But sometimes environmental limits reduce the number of young that survive to reproduce (a negative feedback). Your body is a system with active negative feedback mechanisms: For example, if you exercise, you become hot, and your skin sweats, which cools your body.

Systems may exhibit stability

Negative feedbacks tend to maintain stability in a system. We often think of systems exhibiting **homeostasis,** or a tendency to remain more or less stable and unchanging. Equilibrium is another term for stability in a system. Your body temperature stays remarkably constant despite dramatic changes in your environment and your activity levels. Changing by just a few degrees is extremely unusual—a fever just 4–6°F above normal is unusual and serious. Natural systems such as grasslands can be fairly stable, too. If the climate isn't too dry or too wet, a grassland tends to remain grassland, although the grass may be dense in some years and sparse in others. Cycles of wet and dry years may be part of the system's normal condition.



(a) A simple system



(b) A model of a system

FIGURE 2.11 Systems consist of compartments (also known as state variables) such as fish and plants, and flows of resources, such as nutrients or O_2 (a). Feedback loops (b) enhance or inhibit flows and the growth of compartments.

Disturbances, events that can destabilize or change the system, might also be normal for the system. There can be many kinds of disturbance in a grassland. Severe drought can set back the community, so that it takes some time to recover. Many grasslands also experience occasional fires, a disturbance that stimulates grass growth (by clearing accumulated litter and recycling nutrients) but destroys trees that might be encroaching on the grassland. Thus disturbances are often a normal part of natural systems. Sometimes we consider this "dynamic equilibrium," or a tendency for a system to change and then return to normal.

Grassland plots show **resilience,** an ability to recover from disturbance. In fact, studies indicate that species-rich plots may show more resilience than species-poor plots. Sometimes severe disturbance can lead to a **state shift,** in which conditions do not return to "normal." For example, a climate shift that drastically reduced rainfall could lead to a transition from grassland to desert. Plowing up grassland to plant crops is basically a state shift from a complex system to a single-species system.

Emergent properties are another interesting aspect of systems. Sometimes a system is more than the sum of its parts. For example, a tree is more than just a mass of stored carbon. It provides structure to a forest, habitat for other organisms, it shades and cools the ground, and it holds soil in place with its roots. An ecosystem can also have beautiful sights and sounds that may be irrelevant to its functioning as a system, but that we appreciate nonetheless (fig. 2.12). In a similar way, you are a system made up of component parts, but you have many emergent properties, including your ability to think, share ideas with people around you, sing, and dance. These are properties that emerge because you function well as a system.

Section Review

1. Why are systems important in our environment?
2. What are feedback mechanisms?
3. Describe some emergent properties of ecosystems.

FIGURE 2.12 Emergent properties of systems, including beautiful sights and sounds, make them exciting to study.

2.3 Scientific Consensus and Conflict

- *Science is an incremental process in which many people gradually reach a consensus.*
- *Critical thinking helps us evaluate scientific evidence.*
- *Many people misunderstand the role of uncertainty in science.*

The scientific method outlined in figure 2.3 is the process used to carry out individual studies. Larger-scale accumulation of scientific knowledge involves cooperation and contributions from countless people. Good science is rarely carried out by a single individual working in isolation. Instead, a community of scientists collaborates in a cumulative, self-correcting process. You often hear about big breakthroughs and dramatic discoveries that change our understanding overnight, but in reality these changes are usually the culmination of the labor of many people, each working on different aspects of a common problem, each adding small insights to solve the problem. Ideas and information are exchanged, debated, tested, and retested to arrive at **scientific consensus,** or general agreement among informed scholars.

The idea of consensus is important. For those not deeply involved in a subject, the multitude of contradictory results can be bewildering: Are shark populations disappearing, and does it matter? Is climate changing, and how much? Among those who have performed and read many studies, there tends to emerge a general agreement about the state of a problem. Scientific consensus now holds that many shark populations are in danger, though opinions vary on how severe the problem is. Consensus is that global climates are changing, though models differ somewhat on how rapidly they will change under different policy scenarios.

Sometimes new ideas emerge that cause major shifts in scientific consensus. Two centuries ago, geologists explained many earth features in terms of Noah's flood. The best scientists held that the flood created beaches well above modern sea level, scattered boulders erratically across the landscape, and gouged enormous valleys where there is little water now (fig. 2.13). Then the Swiss glaciologist Louis Agassiz and others suggested that the earth had once been much colder and that glaciers had covered large areas. Periodic ice ages better explained changing sea levels, boulders transported far from their source rock, and the great, gouged valleys. This new idea completely altered the way geologists explained their subject. Similarly, the idea of tectonic plate movement, in which continents shift slowly around the earth's surface, revolutionized the ways geologists, biogeographers, ecologists, and others explained the development of the earth and its life-forms.

These great changes in explanatory frameworks were termed **paradigm shifts** by Thomas Kuhn, who studied revolutions in scientific thought. According to Kuhn, paradigm shifts occur when a majority of scientists accept that the old explanation no longer explains new observations very well. The shift is often contentious and political, because whole careers and worldviews, based on one sort of research and explanation, can be undermined by a new model. Sometimes a revolution happens rather quickly. Quantum mechanics and Einstein's theory of relativity, for example,

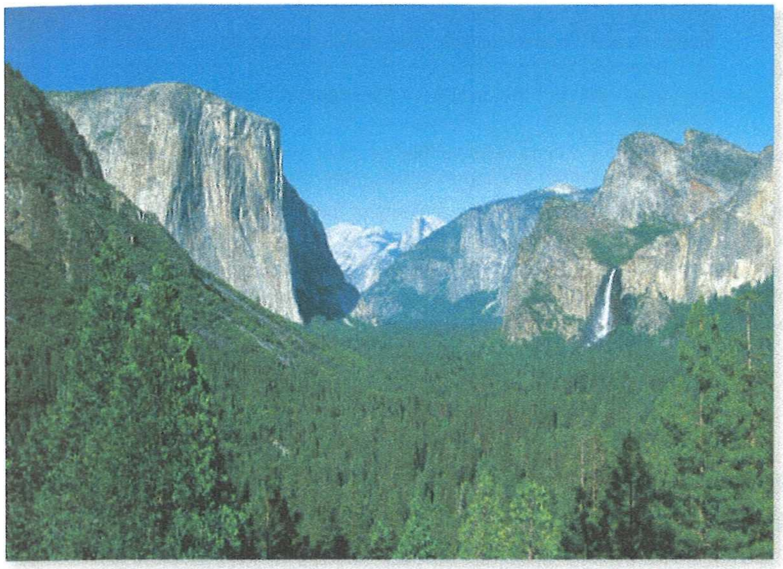


FIGURE 2.13 Paradigm shifts change the ways we explain our world. Geologists now attribute Yosemite's valleys to glaciers, where once they believed events like Noah's flood carved its walls.

overturned classical physics in only about 30 years. Sometimes a whole generation of scholars has to retire before new paradigms can be accepted.

As you study this book, try to identify some of the paradigms that guide our investigations, explanations, and actions today. This is one of the skills involved in critical thinking, discussed in the introductory chapter of this book.

Detecting pseudoscience relies on independent, critical thinking

Ideally, science should serve the needs of society. Deciding what those needs are, however, is often a matter of politics and economics. Should water be taken from a river for irrigation or left in the river for wildlife habitat? Should we force coal-burning power plants to reduce air pollution in order to lower health costs and respiratory illnesses, or are society and our economy better served by having cheap but dirty energy? These thorny questions are decided by a combination of scientific evidence, economic priorities, political positions, and ethical viewpoints.

On the other hand, in every political debate, lawyers and lobbyists can find scientists who will back either side. Politicians hold up favorable studies, proclaiming them "sound science," while they dismiss others as "junk science." Opposing sides dispute the scientific authority of the study they dislike. What is "sound" science, anyway? If science is often embroiled in politics, does this mean that science is always a political process?

Consider the case of climate change. If you judge only from reports in newspapers or on television, you'd probably conclude that scientific opinion is about equally divided on whether climate change is a threat or not. In fact, the vast majority of scientists working on this issue agree that the earth's climate is being affected by human activities, and that threats to the systems we depend on are serious. In a study of 928 papers published in peer-reviewed scientific journals between 1993 and 2003, not one disagreed with the broad scientific consensus on global warming.

Why, then, is there so much confusion among the public about this issue? Why do politicians continue to assert that the dangers of climate change are uncertain at best, or "the greatest hoax ever perpetrated on the American people," as James Inhofe, former chair of the Senate Committee on Environment and Public Works, claims. A part of the confusion lies in the fact that media often present the debate as if it's evenly balanced. The fact that an overwhelming majority of working scientists agree on the issue doesn't make good drama, so some media give equal time to minority viewpoints just to make an interesting fight.

Perhaps a more important source of misinformation comes from conservative foundations and political action funds that finance climate deniers. Between 2002 and 2010, a small group of billionaires donated at least $120 million through secret channels to fund more than 100 think tanks, media outlets, and other groups that promote skepticism about global warming. Some of these organizations sound like legitimate science or grassroots groups but are really only public relations operations. Others are run by individuals who find it rewarding to offer contrarian views. This tactic of spreading doubt and disbelief through innocuous-sounding organizations or seemingly authentic experts isn't limited to the climate change debate. This strategy was pioneered by the tobacco industry to mislead the public about the dangers of smoking. Notably, some of the same individuals, groups, and lobbying firms employed by tobacco companies are now working to spread confusion about climate change.

Given this highly sophisticated battle of "experts," how do you interpret these disputes, and how do you decide whom to trust? The most important strategy is to apply critical thinking as you watch or read the news. What is the agenda of the person making the report? What is the source of their expertise? What economic or political interests do they serve? Do they appeal to your reason or to your emotions? Do they use inflammatory words (such as "junk"), or do they claim that scientific uncertainty makes their opponents' study meaningless? If they use statistics, what is the context for their numbers?

It helps to seek further information as you answer some of these questions. When you watch or read the news, you can look for places where reporting looks incomplete, you can consider sources and ask yourself what unspoken interests might lie behind the story.

Another strategy for deciphering the rhetoric is to remember that there are established standards of scientific work, and to investigate whether an "expert" follows these standards: Is the report peer-reviewed? Do a majority of scholars agree? Are the methods used to produce results well documented?

Harvard's Edward O. Wilson writes, "We will always have contrarians whose sallies are characterized by willful ignorance, selective quotations, disregard for communications with genuine experts, and destructive campaigns to attract the attention of the media rather than scientists. They are the parasite load on scholars who earn success through the slow process of peer review and approval." How can we identify misinformation and questionable claims? The astronomer Carl Sagan proposed a "Baloney Detection Kit" to help identify questionable sources and arguments (table 2.2).

Most scientists have an interest in providing knowledge that is useful, and our ideas of what is useful and important depend partly on our worldviews and priorities. Science is not necessarily political, but it is often used for political aims. The main task of educated citizens is to discern where it is being misused or disregarded for purposes that undermine public interests.

Section Review

1. Why do we say that proof is elusive in science?
2. How can we evaluate the validity of claims about science?
3. What is the role of consensus in science?

Table 2.2 Questions for Baloney Detection

1.	How reliable are the sources of this claim? Is there reason to believe that they might have an agenda to pursue in this case?
2.	Have the claims been verified by other sources? What data are presented in support of this opinion?
3.	What position does the majority of the scientific community hold in this issue?
4.	How does this claim fit with what we know about how the world works? Is this a reasonable assertion or does it contradict established theories?
5.	Are the arguments balanced and logical? Have proponents of a particular position considered alternate points of view or only selected supportive evidence for their particular beliefs?
6.	What do you know about the sources of funding for a particular position? Are they financed by groups with partisan goals?
7.	Where was evidence for competing theories published? Has it undergone impartial peer review or is it only in proprietary publication?

Conclusion

Science is a process for producing knowledge methodically and logically. Scientists try to understand the world by making observations and trying to discern patterns and rules that explain those observations. Scientists try to remain cautious and skeptical of conclusions, because we understand that any set of observations is only a sample of all possible observations. In order to make sure we follow a careful and methodical approach, we often use the scientific method, which is the step-by-step process of forming a testable question, doing tests, and interpreting results. Scientists use both deductive reasoning (deducing an explanation from general principles) and inductive reasoning (deriving a general rule from observations).

Hypotheses and theories are basic tools of science. A hypothesis is a testable question. A theory is a well-tested explanation that explains observations and that is accepted by the scientific community. Probability is also a key idea: Chance is involved in many events, and circumstances can influence probabilities—such as your chances of getting a cold or of getting an A in this class. We often use probability to measure uncertainty when we test our hypotheses.

Models and systems are also central ideas. A system is a network of interdependent components and processes. For example, an ecosystem consists of plants, animals, and other components, and energy and nutrients transfer among those components. Systems have general characteristics we can describe, including throughput, feedbacks, homeostasis, resilience, and emergent properties. Often we use models (simplified representations of systems) to describe or manipulate a system. Models vary in complexity, according to their purposes, from a paper airplane to a global circulation model.

Science aims to foster debate and inquiry, but scientific consensus emerges as most experts come to agree on well-supported theoretical explanations. Sometimes new explanations revolutionize science, but scientific consensus helps us identify which ideas and theories are well supported by evidence, and which are not supported.

Reviewing Key Terms

Can you define the following terms in environmental science?

science
reproducibility
replication
significant number
deductive reasoning
inductive reasoning
hypothesis
scientific theory
natural experiment
manipulative experiment
controlled study
blind experiment
double-blind experiment
dependent variable
independent variable
models
systems
open systems
closed system
throughput
positive feedback
negative feedback
homeostasis
disturbances
resilience
state shift
emergent properties
scientific consensus
paradigm shifts

Critical Thinking and Discussion Questions

1. Explain why scientific issues are or are not influenced by politics. Can scientific questions ever be entirely free of political interest? If you say no, does that mean that all science is merely politics? Why or why not?
2. Review the questions for "baloney detection" in table 2.2, and apply them to an ad on TV. How many of the critiques in this list are easily detected in the commercial?
3. How important is scientific thinking for you, personally? How important do you think it should be? How important is it for society to have thoughtful scientists? How would your life be different without the scientific method?
4. Many people consider science too remote from everyday life and from nonscientists. Do you feel this way? Are there aspects of scientific methods (such as reasoning from observations) that you use?
5. Many scientific studies rely on models for experiments that cannot be done on real systems, such as climate, human health, or economic systems. If assumptions are built into models, then are model-based studies inherently weak? What would increase your confidence in a model-based study?

Data Analysis

Evaluating Uncertainty

Uncertainty is a key idea in science. We can rarely have absolute proof in experimental results, because our conclusions rest on observations, but we only have a small sample of all possible observations. Because uncertainty is always present, it's useful to describe how much uncertainty you have, relative to what you know. It might seem ironic, but in science, knowing about uncertainty increases our confidence in our conclusions.

The graph on the next page is from a landmark field study by D. Tilman et al. It shows change in biomass within, experimental plots containing varying numbers of native prairie plants after a severe drought. Because more than 200 replicate (repeated test) plots were used, this study was able to give an estimate of uncertainty. This uncertainty is shown with error bars. In this graph, dots show means for groups of test plots; the error bars show the range in which that mean could have fallen, if there had been a slightly different set of test plots.

Let's examine the error bars in this graph. To begin, as always, make sure you understand what the axes show. This graph contains a lot of information, so be patient.

Questions:

1. What variable is shown on the X-axis? What are the lowest and highest values on the axis?
2. Each dot shows the average species count for a set of test plots with a given number of species. About how many species in the plots are represented by the leftmost dot? By the rightmost dot?
3. What is the axis label on the Y-axis? What does a value of 0.75 mean? A value of 1.0?

   (Note: the Y-axis doesn't change at a constant rate. It changes logarithmically. This means values at the low end are more visible.)
4. Each blue dot represents a group of plots with 5 or fewer species; red dots represent plots with more than 5 species. Look at the leftmost dot, plots with only 1 species. Was biomass less or more after the drought?

   The error bars show standard error, which you can think of as the range in which the average (the dot) might fall, if you had a slightly different set of plots. (Standard error is just the standard deviation divided by the square root of the number of observations.) For 1-species plots, there's a small chance that the average could have fallen at the low end of the error bar, or almost as low as about 0.5, or half the pre-drought biomass.
5. How many of the blue error bars overlap the dotted line (no change in biomass)? How many of the red error bars overlap the dotted line? Are there any red bars entirely above the 1.0 line?

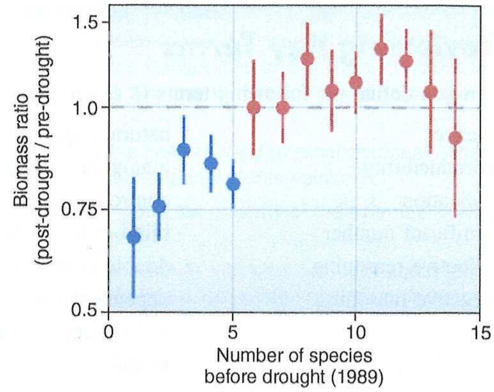


FIGURE 1 Mean ratio of biomass after and before a drought (dots). Vertical bars show standard error of the mean for vegetation plots planted with different numbers of species. for Regrowth after a drought was poorer for plots with five or fewer species (blue) than for more diverse plots (red).

Where the error bars fall entirely below 1, we can be quite sure that, even if we had had a different set of plots, the after-drought biomass would still have declined. Where the error bars include a value of 1, the averages are not significantly different from 1 (or no change).

The conclusions of this study rest on the fact that the blue bars showed nearly-certain declines in biomass, while the red (higher-diversity) bars showed either no change or increases in biomass. Thus the whole paper boiled down to the question of which error bars crossed the dotted line! But the implications of the study are profound: they demonstrate a clear relationship between biodiversity and recovery from drought, at least for this study. One of the exciting things about scientific methods, and of statistics, is that they let us use simple, unambiguous tests to answer important questions.

connect ENVIRONMENTAL SCIENCE

FOR ADDITIONAL HELP IN STUDYING THIS CHAPTER, PLEASE VISIT OUR WEBSITE AT www.mhhe.com/cunningham13e.

You will find practice quizzes and case studies, flashcards, regional examples, placemarkers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.