CHAPTER 1 The Nature of Science

Science is a lie detector.
—Brian L. Silver (1998:20)

Science . . . is the organized, systematic enterprise that gathers knowledge about the world and condenses the knowledge with testable laws and principles.
—Edward O. Wilson (1998:53; emphasis in original)

The central aim of science is to render the complexities of the universe transparent, so that we can see through them to the simplicities beneath.
—Jack Cohen and Ian Stewart (1994:29)

Science ranges across a vast panorama of endeavor. At one extreme of the range, we have detailed description, generally associated with atomization of subject matter (reductionism): particle physics, chemistry, molecular genetics, cell biology. At the other extreme we have the study of small to large systems: Newtonian mechanics, thermodynamics, natural selection, cosmology. The reductionists work with parts; the systematists with the expression of emergent properties and underlying principles of interacting parts. Thus, science as a body of tasks ranges from micro description to macro generalization and includes all possible levels of detail and grand sweep between these bounds.

Despite the diversity of scientific enterprise, there are common themes in all of science. These include underlying assumptions and philosophies as well as the normal activities of scientists. The activities include description of phenomena, pattern finding, hypothesis formulation, hypothesis testing, theory development, and methods development and testing. Of course, the greatest common denominator across science is thinking. Use of the mind alone leads to the discovery of great flaws in thinking and the production of great insight. This chapter introduces the common themes in science, including natural resource science.

Basic Assumptions and Philosophy

"In the methodology and the practice of science are many assumptions of value" (Houghton 1994:148). "For instance, that there is an objective world of value out there to discover, that there is value in the qualities of elegance and economy in scientific theory, that complete honesty and cooperation between scientists are essential to the scientific enterprise."

Houghton's statement reflects the philosophical infrastructure of science under modernism (a philosophy that arose in the eighteenth century and that implied reason and science rather than superstition and faith should be used to understand nature). The key assumption is that "there is an objective world of value out there." If the assumption holds, then there is objective truth out there and it is the quarry of scientists. However, the history of science teaches that accepted truth changes as explicit and implicit assumptions fail, accuracy of measurement improves, methodological bias becomes apparent, and knowledge expands. "The road to truth is always under construction; the going is the goal" (Berman 2000:138).

Postmodernists take a different view of scientific knowledge. They view knowledge as largely an outcome of zeitgeist (the spirit and values of the times) and the cultural affiliation of scientists (Gross and Levitt 1994). Based on that premise, they say scientific knowledge does not represent objective truth. Their arguments have some merit because human values (desires) and sociality hang like a pall over the accrual of objective knowledge.

Scientists, of course, must be aware of human shortcomings, especially their own, in the search for reliable knowledge. I will elaborate these ideas more fully in chapter 5. Scientists are, to a lesser or greater degree, subject to greed, vanity, egocentrism, and tribe allegiance. Human values and vested interest pollute the search for reliable knowledge. These foibles limit what scientists do perceive and even what they *can* perceive. The foibles lead inevitably to the formulation and propagation of false knowledge, which Romesburg (1981:293) defined as "false ideas that are mistaken for knowledge."

Based on the assumption of an objective reality available for discovery, the philosophers of science have done considerable reasoning on how to discover that reality. *Reasoning* is a key word here, for their ideas are perforce based on thought. They use formal logic to judge the relative merit of induction (generalizing from a specific event) and deduction (predicting a specific event from a generalization). We will discuss these topics more fully in chapter 3. Suffice it to say at this point that both induction and deduction are essential concepts in the practice of science.

Another assumption mentioned by Houghton (1994:148) is "that there is value in the qualities of . . . economy in scientific theories." The desirability of economy, or simplicity, is widely accepted among scientists. The idea owes to William of Ockham (or Occam), a fourteenth-century Franciscan, who wrote, "What can be explained by the assumption of fewer things is vainly explained by the assumption of more things" (Silver 1998:169). This principle has come to be known as Ockham's Razor, the principle of parsimony, or the principle of economy. The practical ramification of Ockham's Razor is that if you have a set of hypotheses that explain an event in nature equally well, the simplest hypothesis with respect to assumption tally is the best of the set (most likely to be true). Nowadays, hypotheses are said to be simpler if they entail fewer steps in a cause-effect chain, fewer parameters in a model, fewer assumptions, or, in general, fewer conditions to explain or predict.

As an example of the application of Ockham's Razor, consider the general observation that animals on a good nutritional plane tend to survive better and produce more young than animals on a poor nutritional plane. Now consider the fact that northern bobwhites (*Colinus virginianus*) tend to be poor survivors and good producers in northern latitudes, whereas they tend to be good survivors and poor producers in southern latitudes (Guthery 1997; Guthery et al. 2000). To explain the latter observation in terms of nutrition, we would have to hypothesize that summer foods are more nutritious and winter foods less nutritious in northern latitudes, whereas winter foods are more nutritious and summer foods less nutritious in southern latitudes. We might pit these hypotheses against the observation that winters are relatively severe in northern latitudes, whereas summers are relatively severe in southern latitudes. A weather hypothesis for explaining latitudinal patterns in bobwhite demography is simpler than the nutrition hypothesis and therefore takes precedence under Ockham's Razor.

Statistical modeling of the relation between dependent and independent variables provides another application of the principle of parsimony. Suppose we have data on a variable y that is some function of a variable x. We have 3 competing models:

$$y = a + bx,$$
$$y = \exp(a + bx), \text{ and}$$
$$y = a + bx + cx^2.$$

The constants (a, b, c) in these models represent parameters that must be estimated. The first 2 models are equally parsimonious because each has 2 parameters, whereas the third model has 3 parameters. Thus, if each of these models explained a relationship equally well, the researcher would reject the third model (most complex) on the basis of parsimony. I will address model selection in greater detail in chapter 11.

Ockham's Razor is a useful principle for reasons of likelihood. On the one hand, the simplest hypothesis in a set of hypotheses may be the least likely to appear out of the blue, so it must be closer to the truth than the alternatives (Feynman 1998). Newton's inverse square law of gravitational attraction was regarded by Feynman as a concept so simple that it must be true. Diamond's (1997) conjecture that the cultural effects of crop domestication spread more easily along longitudinal than latitudinal gradients is singular in its simplicity. (This would occur because a domesticated plant may have a greater longitudinal than latitudinal range where it is adapted to prevailing climate.)

On the other hand, the simplest hypothesis may be the most likely to appear. "Facts" as we know them are problematic (chapter 4). Facts might have truth-values <1, implying they are not completely true (truth-value $= 1$). It follows that a longer chain of facts leading to an outcome would be expected to have lower truth-values than a shorter chain. Suppose the truth-value of a hypothesis is correlated with the product of truth-values in a chain of explanations. If all the facts in a chain of events had a truth-value of 0.9, then a 2-event chain would have a truth-value proportional to $0.9^2 = 0.81$, whereas a 5-event chain would have a truth-value proportional to $0.9^5 = 0.59$. The shorter chain (2 events) is more likely than the longer chain (5 events). For this reason, molecular taxonomists rely on the most parsimonious evolutionary tree (the one with the smallest number of changes) to explain relationships between and among taxonomic units (Avise 1994:122).

Bear in mind, however, that application of Ockham's Razor represents failure, for knowing truth, a scientist would not have to invoke a mildly metaphysical standard of judgment. Indeed, perhaps the razor should be called Ockham's Crutch. Oreskes et al. (1994:645) argued that

> Ockham's razor is perhaps the most widely accepted example of an extraevidential consideration [in model selection]. Many scientists accept and apply the principle in their work, even though it is an entirely metaphysical assumption. There

> is scant empirical evidence that the world is actually simple or that simple accounts are more likely than complex ones to be true. Our commitment to simplicity is largely an inheritance of [fourteenth-century] theology.

I disagree with Oreskes et al. to a degree because, as I argued above, there are logical reasons to expect simpler is better, given some universe of discourse. However, the simplest hypothesis or model is not necessarily the best hypothesis or model. Ockham's Razor probably becomes less useful as the complexity of a research topic increases. "Nowhere is [Ockham's] Razor more misplaced," for example, "than in a science of culture" (Plotkin 2000:80). Ecosystems, like cultures, are complex, so the natural resource scientist should regard Ockham's Razor as, at best, a prosthesis for amputated scientific endeavor. The natural resource scientist must *judge* both the complexity and power of hypotheses when accepting or rejecting competing alternatives.

Major Activities of Scientists

Description

All forms of science have descriptive underpinnings, and natural resource science is no exception. Description is based on motive—desire to know—rather than hypothesis. Description is essential because it is impossible to conduct other processes of science (e.g., hypothesis formulation) without a bank of descriptive data. Ideas do not spontaneously appear without observations; for example, try thinking of something about nothing.

In natural resource science, descriptive studies (natural history) address topics such as diet, reproduction (e.g., clutch size, litter size), behavior, habitat use, mobility and ranges, and so on. Natural history originally meant natural description (Schmidly 2005). The results of natural history research could be viewed as the mathematical logic of field biology in that the facts gathered probably are as pure as any facts in field biology. Descriptive data are necessary fodder for thought, and they may yield insight and original research questions.

For example, my research team recently obtained descriptive data on temperature dynamics in bobwhite nests (Guthery, Ryback, et al. 2005). Temperatures showed considerable variation, and the average temperature was well below that recommended for artificial incubation, which takes place at a constant temperature. We wondered whether there might be some fitness benefit associated with variable egg temperatures, and whether temperature variation might be associated with higher hatching rates in artificial incubators. The point is that the descriptive results generated the questions.

The estimation of magnitudes of effects is a form of descriptive science. Effect estimation is appropriate when a relationship is known or a treatment has known effects but the strength of the relationship or the size of an effect is in question. This type of simple descriptive study is common in natural resource science, although it often is camouflaged with mundane hypotheses, gratuitous predictions, and statistical folderol.

For example, there is no doubt that protein is an essential nutrient for reproduction in wild animals. Thus, a study of protein effects on reproduction provides yet another estimate of the degree to which different protein levels affect a reproduction variable. Likewise, many relationships are known to exist in nature and need not be tested per se. The strength (magnitude) of a relationship might be in question. Studies of the response of wildlife individuals or populations to management treatments are often an exercise in estimating the magnitudes of effects. It is somewhat silly to suppose researchers would test a treatment if they expected it to have no effect.

Descriptive results serve additional purposes in science. Collections of descriptive data are indispensable because they may lead to the discovery of patterns (trends or recurrences). The patterns discovered, or the descriptive data per se, might lead to explanations (how) or hypotheses on cause (why).

Pattern Finding

When several bodies of descriptive data have accumulated, the natural resource scientist is positioned to search for prevailing patterns in the knowledge base (synthesize). How does one search for patterns in published research? Obviously, one has to become cognizant of the relevant information (i.e., study it) that has accumulated on some topic, abstract saliencies from that information, and discern patterns, if possible. Constructing maps, figures, or tables from existing results may facilitate insight.

A classic example of pattern finding in the annals of science involves the periodic table of the elements (Bronowski 1973:322–26). Dmitri Ivanovich Mendeleev, a Russian chemist, wrote the names and atomic weights of elements on note cards and laid out the cards according to patterns of atomic weights. This revealed families of ele-

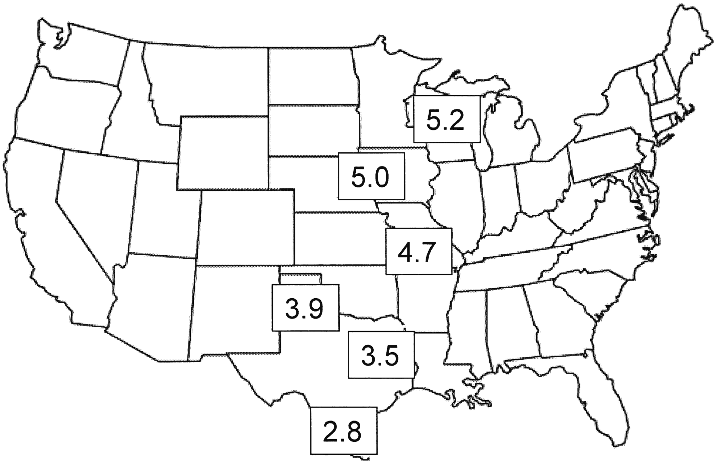

Fig. 1-1 Latitudinal trends in autumn age ratios (juveniles/adult) in midcontinent populations of northern bobwhites. The graphic shows a pattern (latitudinal gradient) in production and, by inference, survival rates.

ments with similar chemical properties. Mendeleev had the presence of mind to recognize gaps in the data—chemical elements that would later be discovered.

As a personal example of pattern finding, I came to recognize from the descriptive literature that age ratios of northern bobwhites were higher in northern latitudes and lower in southern latitudes. I constructed a graphic to illustrate this aspect of bobwhite demography (Guthery 2000; Fig. 1-1). The mere act of plotting age ratios at the approximate locations where samples were collected revealed a remarkable association (pattern) between latitude and productivity. Because, under mild assumption, average annual age ratios contain information on annual mortality rates (the percentage of juveniles reflects the annual mortality rate in populations with known trends), the graphic simultaneously revealed an association between latitude and annual mortality rates. The simple geographic pattern had broad implications on theories of bobwhite demography and harvest management (Guthery et al. 2000).

Hypothesis Formulation

"The classical procedure in science is to formulate a hypothesis and then carry out an experiment that is capable of disproving it" (Alexander 1996:146). We will see in the next chapter that the word *hypoth-*

esis has different meanings in science. At this point, we can define hypothesis as a tentative explanation for something; the explanation serves as the basis for further research.

Why should we be concerned that an experiment can disprove a hypothesis? Because if a hypothesis or theory conceivably can be disproved by observation or experiment, if it is testable, then it might well belong in the realm of science. Testability (falsifiability) is Popper's (1959:78) criterion of demarcation between scientific and nonscientific hypotheses. If not testable, a hypothesis might belong in the realm of faith or metaphysics (attempts to understand nature with pure reason). As we shall see in chapter 2, however, untestable hypotheses can be useful in science.

As with any principle or protocol of science, the criterion of testability should not be accepted blindly. "Popper's criterion . . . does demarcate between empirical [based on measurement or observation] and metaphysical statements," observes Skrabanek (2000:116), "but it is so wide that it allows non-metaphysical nonsense to slip in." For example, early Europeans thought children with Down syndrome occurred when a human being mated with a werewolf (*Canis quirkii;* Lopez 2004). Surely this hypothesis is testable with molecular genetics analysis, but just as surely it is nonsense. Finally, some theorems of mathematics such as Bernoulli's Law of Large Numbers cannot be tested, but we judge them scientific. (Bernoulli's Law states, approximately, that if the probability of an event is p, the relative frequency of the event will approach p in repeated independent trials as the number of trials approaches huge numbers.)

Moreover, sometimes we are less interested in a claim's testability than its heuristic value (Sorenson 1992:97), in which case testability is not especially germane. A claim has heuristic value (encourages discovery) if it leads to original thinking and alternative hypotheses. For example, Gause's Competitive Exclusion Principle is not testable (Sinclair 1991) but it is a metaphysical springboard for further thought on ecological competition. Indeed, twenty-first-century science is a blend of metaphysics and empiricism (Seager 2000).

At a minimum, the formulation of a testable hypothesis entails the availability of observations in need of explanation. The scientist then conjectures on whether a phenomenon exists, how it can be explained, or why it came to pass. Hypothesis formulation is, accordingly, a matter of pure thought as influenced by the ideas held in a mind.

Hypothesis Testing

Some forms of legitimate natural resource science do not entail hypothesis testing (Guthery, Lusk, et al. 2004). Natural history and estimation of magnitudes of effects are examples. In the former case the acquisition of descriptive information justifies the study, and in the latter case an effect or relationship is already known based on existing knowledge.

Hypothetico-deductive (H-D) experimentation is the classical method of testing a hypothesis. It involves formulating a hypothesis and deducing events that will be observed under experimentation if the hypothesis is true: "If my conjecture on explanation or cause is true, then I expect to observe these outcomes in an experiment." For example, "If salmon (*Oncorhynchus* spp.) use olfaction to navigate to natal streams, then (I deduce) streams will have unique chemical signatures." Unique chemical signatures would be requisite for salmon to navigate to a specific stream by olfaction. If the deduction, or prediction, is observed, then the hypothesis is supported by experimental results. Otherwise, it is not supported. In application in field ecology, the H-D method has flaws that we will discuss in chapter 3.

A large body of statistical tools has been developed for testing null (no effect) hypotheses. These include significance testing based on test statistics such as t and F. These tools and others like them were developed because we encounter variability in research results, which leads to uncertainty. The variability might occur because we have imprecise measurements, incomplete knowledge of causes, and/or some combination of these and/or other factors. The statistical tools provide logical, mathematical methods of dealing with uncertainty en route to conclusions. A common property of all such tools is a direct or indirect basis in probability. Scientists, accordingly, may judge the merit of hypotheses (some say adjust their beliefs about a hypothesis) relative to whether the hypotheses are probable or improbable based on observation and analysis.

Rational scientists should view statistical tools as purveyors of evidence upon which to base *judgments.* All such tools are based on assumptions that might or might not be relevant in understanding nature; the null hypothesis is seriously flawed (chapter 10). No such tool can override the effects of poor experimental design, human bias, or idiosyncratic data (data that, for one reason or another, poorly reflect the state of nature at the time of data collection).

Theory Development

After a hypothesis has passed repeated and severe challenges, it may become a theory. "A theory is a good theory if it satisfies two requirements: It must accurately describe a large class of observations [patterns] on the basis of a model that contains only a few arbitrary elements [simplification], and it must make definite predictions about the results of future observations" (Hawking 1988:9). Theories abstract "what is regular and readily reproducible from reality and present it in idealized form, valid only under certain assumptions and boundary conditions" (Eigen and Winkler 1981:16). An important process of science is the hewing of simplicity from complexity through theory development (Atkins 1995:126), the compression of information on offer into simple models with explanatory or predictive power (Barrow 1995:47).

A few simple rules, the stuff of theory, may lead to extremely complex outcomes. As an analogy, Russell (2000) claims mathematics in all its complexity and intricacy arose from about 12 primitive notions. The chore of ecological scientists is to find the few primitive notions from which we can deduce all the clamor of nature. Darwin's theory of natural selection is an example of a powerful primitive notion that is relevant to ecology. There is no higher pinnacle in scientific achievement than to discover simple rules that explain complex behaviors.

Development and Testing of Methods and Techniques

Many papers in natural resource journals involve the development and testing of methods and techniques. Such work might involve an assessment of the merit of different estimators of a particular variable. For example, numerous papers have evaluated different estimators of home range size. New methods of estimating or analyzing different variables or situations continuously arise from the human mind; these, in turn, need to be assessed for strengths and weaknesses. When new technologies such as global positioning systems appear, their performance under field conditions needs to be evaluated. I view methods research as more technological than scientific. Nonetheless, scientists need to understand the tools they apply. As methods research leads to improved measurement of variables, this, in turn, leads to improved reliability of the knowledge gained from measurement.

The Role of Mind

Scientific knowledge is, above all else, a product of the human mind. It has the ability to ask innocent questions with catastrophic answers, to recognize patterns and synthesize, to imagine things that do not really exist but that help us understand, and to speculate on explanations or causes based on the repository of knowledge available at the time. Too often scientists let the trappings of science—experimental design, statistical testing, model selection—take precedence over the application of good old-fashioned thought. There is a natural human tendency to confuse means (e.g., statistical tests) with ends (e.g., reliable knowledge), and that tendency is well illustrated in natural resource science (chapter 14).

In the philosophy of science, there have been two opposing views on how knowledge comes to be. Rationalism is the theory that the intellect is the true source of knowledge, whereas empiricism is the theory that sensory experience is the only source of knowledge. The practicing scientist must blend these theories to generate useful new knowledge. That is, the scientist must develop thoughts about phenomena (rationalism) and put those thoughts to experimental or observational test (empiricism).

Perspectives

This chapter is a bare-bones introduction to the nature of science, about which tomes have been written. Nonetheless, it raises important issues. The student of natural resource science should take note that 2 supposed canons of science—Popper's criterion of demarcation and Ockham's Razor—are incomplete if not imperfect. Yet the student will find that many members of the scientific community hold them in high esteem if not awe; the concepts are part of the religion of science. The phrase "testable hypothesis," for example, has become a shibboleth (a password that allows your entrance into the culture). Excepting honesty and integrity, there probably are few protocols of science that cut unconditionally across the practice. We will see additional much-revered though somewhat bastard standards and principles as the book unfolds.

Chapter 1 also sets up several of the topics that follow. In particular, the chapter introduces both hypothesis formulation as an important activity of scientists and the different types of hypotheses that may be formulated.