Scientific Method for Ecological Research

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Contents

1 Component processes of ecological research

Summary

Ecologists starting research for the first time have many questions about the scientific method. This chapter gives examples of these questions and classifies them into three groups: those concerned with the analytical process of research; those concerned with the special problems of ecology, particularly how we synthesize knowledge and develop ecological theory; and those concerned with the social aspects of research. The chapter describes how these groups of questions will be answered in successive sections.

SECTION I

Developing an analytical framework. A logical framework is required for research. Assumptions must be clearly stated as axioms, and questions must be formed as postulates, i.e., statements that can be investigated and then classified as true or false, or assigned a probability. This framework is the foundation for the research you do and the basis for making scientific inference.

SECTION II

Making a synthesis for scientific inference. Ecological and environmental research present special problems of scientific methodology. Ecological systems are open to multiple influences and vary in ways that limit the types of investigation used and the generality of scientific inference that can be made. Some important concepts have to be defined by a theory.

SECTION III

Working in the research community. Social interactions influence the scientific method. Science is, in part, a social activity that can influence how, and what, problems are researched.

SECTION IV

Progressive Synthesis is defined as a methodology for developing ecological theories and examining how coherent they are as explanations.

A distinction is drawn between what scientists do in research (the progress they make) and how it should be done (the processes that should be used). Progress comes from continuous dialogue between our theories about the world and the measurements we make that result in the synthesis of new or improved theories. To energize this dialogue, we use four processes: creativity, definition, assessment, and, most important, critical analysis. Critical analysis is a foundation for creativity because it reveals what may be wrong or deficient in definitions and assessments and what must be reconstructed.

1.1 Questions about the process of scientific research

Scientific discovery has a particular satisfaction. The joy of discovery – ''Here is something new!'' – is heightened by the realization that what has been created through research increases or changes the knowledge developed by other scientists. Furthermore, a new discovery may make it possible to solve a practical problem. These components, a discovery that is relevant to other knowledge and that may have practical value, make science an exciting and rewarding creative activity.

Many ecologists starting research have questions about the scientific method and how to apply it, whether it really works for ecology, and how the scientific community functions collectively in making discoveries (Table 1.1). Those who gave the questions for Table1.1 were embarking on research in basic ecology, the conservation and management of natural resources, and environmental sciences. Despite the diverse nature of their research topics, the questions show repeated concerns about three components of the research process:

(1) *How to develop a conceptual and logical framework for discovery and assessment* (Questions 1–21, Table 1.1). Many students have a practical question they wish to answer or a subject they wish to research. However, it can require considerable analysis to define how a piece of research should proceed, what should be measured, how investigations should be carried out, and what process should be used for making scientific inference.

(2) *How to approach the particular difficulties associated with ecological and environmental research* (Questions 22–25, Table 1.1). Ecological systems present particular difficulties to the research scientist. Their variability can make them difficult to sample, but this variability is not simply a nuisance. It is a fundamental characteristic of ecological systems! For example, at the organism and population levels, genetic variability and plasticity in development are inherent characteristics. At the community or ecosystem level, differences in local environment or history can make an ecological system unique in an important way that

Table 1.1. *Questions asked by ecology students at the start of a graduate course in the scientific method. These questions are complete and as they were written by students. Questions 16 and 17 contain misuses of the terms "hypothesis" and "prove". See Chapters 3, 7, and 8 for correct definitions and examples of use*

I. Questions about research planning and the scientific method

1. How can I come up with a question?
2. I have ideas and topics but I don't have a project.
3. How can I refine a question so that an answer can be obtained?
4. I have a project. Can I find an innovative way to look at the problem? Can I find a way where others have not?
5. When starting research how do we know what analogies to use? How to get new ideas?
6. Am I making a significant contribution to the body of knowledge?
7. I have my project – but have I missed anything out?
8. How will I know whether I am duplicating other research?
9. How will I know whether my project is relevant or significant to a theory or a practical question, or just a stupid idea?
10. How can I conduct a literature review? How will I know what research is going on, what has been done? What about research in a foreign language?
11. How will I know whether my project is too big or too small?
12. How can I confine the question so that it is a Master's topic and not a lifetime of study?
13. How will I know when to stop (as an individual) given the cyclical nature of science?
14. How do I limit the project so that it can be finished in two years?
15. How will I analyze my data and write my thesis? How will I know what to conclude? Have I got there?
16. You make a hypothesis, and then you try to prove it. What if it is incorrect?
17. We start by trying to prove a hypothesis, but we end up trying to fit a new hypothesis to the data?
18. Will I collect bad data, or data insufficient to answer the question?
19. Some questions have answers. Some problems are exploratory. How do you present the exploratory work? This is difficult because the scientific culture expects answers.
20. What types of control or experimental design will I need?
21. How can I interpret my results in an unbiased way so that I do not massage my results to fit any preconceived viewpoint?

II. Questions about research in ecological science

22. How can I ask the right question and measure the right things? How can I sample a whole ecosystem? How can I avoid samples being influenced by unusual events?
23. How do we extrapolate from research on a limited system (laboratory or field plot) to give an understanding of a whole ecosystem?
24. How can I find a place (site) where a question can be answered? There may be difficulty matching a proposed theory with practical reality.
25. Which techniques are the best for measuring the response of a tree to environmental factors? For example, the development of a bioassay?

Table 1.1. (*cont.*)

III.	**Questions about working in the research community**
26.	Can I get funded?
27.	Funding!
28.	I am interested in funding and individual recognition.
29.	How do I choose a committee that will give me a broadly based opinion?
30.	How can I get my committee to stop suggesting things to do?
31.	What if my committee steers me incorrectly?
32.	How can I analyze, integrate, and present to the outside world?
33.	How can I choose a research topic of value? Or if you have chosen a research topic how can you persuade someone to fund it?
34.	How can I make research relevant to current topics of theoretical and practical interest?

must be taken into account in a research study. Because of this variability, research in ecology can involve two phases of activity: (a) discovering a phenomenon or process and developing a theory that explains it, and (b) understanding how important that phenomenon or process is in different situations.

(3) *How to work within the scientific and natural resource management communities* (Questions 26–34, Table 1.1). Supervisors, major professors, and associated faculty and colleagues influence a student's research through their distinct research perspectives, which the student must identify and weigh. Local, state, or national agencies frequently fund ecological and environmental research, and social factors influence who receives grants or contracts from them. In addition, much ecological research investigates practical problems of environmental management with the objective of providing solutions. Almost inevitably, any proposed solution will have an economic or social impact on someone or may run counter to his or her ideals. Even the possibility that this may happen can influence what research is proposed and how it is conducted.

1.2 Scientific methodology

This book presents a methodology for scientific research.

METHODOLOGY

A system of techniques of investigation, methods for applying the techniques, and general principles for how the methods should be used in scientific inquiry.

Techniques of investigation used in research, such as experimentation, survey, or constructing computer models, must be applied using methods that ensure an effective process of scientific reasoning. Principles, such as the continuous use of criticism and being explicit in definitions and methods of assessment, must be used consistently for all techniques and methods.

The first objective of this book is to provide a structure for the process of scientific reasoning and research planning. The second is to illustrate particular problems in ecological research that determine how different techniques of research can be used and show how careful we must be in our methods of using these techniques. The third is to discuss how social influences can affect scientific research. In this respect ecological research faces some particularly difficult challenges when a problem is important for resource or environmental management.

1.3 Distinction between progress and process in scientific research

The foundation for answering the questions in Table 1.1 is to recognize that scientific research has two parts. (1) What scientists do – the techniques they apply to solve problems and make progress. (2) How scientists think – the thought processes scientists use in analyzing a problem.

(1) *What scientists do.* Scientists analyze problems and then make investigations and/or conduct experiments to discover new information. They order and explain this information in a synthesis by producing theories of how the world works. Theories are the result of a dialogue between what we think we know (our previous theories), and what we see or measure in the world (our data). It takes effort to become proficient in particular techniques of investigation, e.g., ecological field experiments, vegetation survey and analysis, and to understand how theories are constructed with information obtained by using them. Not surprisingly the research questions we choose, and the way we analyze them, may be strongly influenced by the techniques of investigation we have mastered. The theories we construct, or rate as most valuable, may be biased towards information obtained from the techniques of investigation with which we are most familiar. The challenge we face is that theory and data are interlinked (Fig. 1.1), and this circular nature of investigation can strongly influence what we find out – even when we think we are approaching new problems. This is why problem analysis is so important at the start of research.

(2) *How scientists think.* The repeated dialogue scientists conduct between THEORY and DATA requires critical analysis and creativity. Definition and assessment must be in constant interaction: we define our ideas

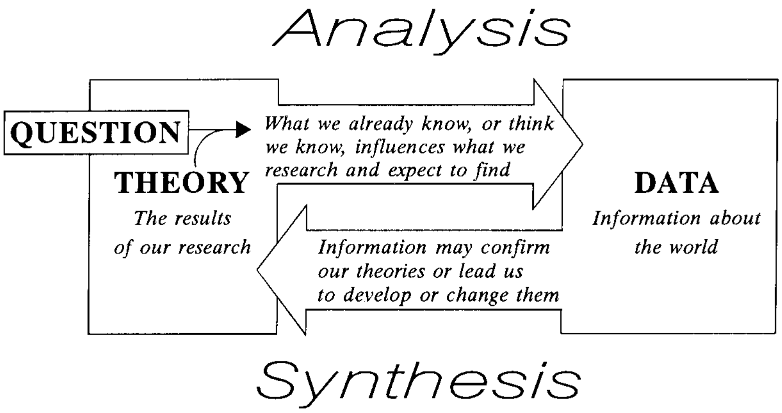

Fig. 1.1. The cycle of scientific investigation. Although scientists use data to assess theories, the type of data they collect is determined by those theories. Analyzing a scientific theory so that it can be questioned by data is a major challenge for the scientist.

as a theory, develop new ideas from the theory, assess those ideas using measurements, and redefine the theories in a new synthesis. However, the interaction between definition and assessment must be pushed, prodded, and cajoled by critical analysis. Critical analysis is the fundamental process we must continually apply to make definitions exact and unambiguous, and assessments unbiased (Fig. 1.2).

Criticism is an essential foundation for creativity. This may at first seem counterintuitive; we often associate criticism with destruction, the opposite of creativity. But discovering something new may first require realizing that a current theory or set of observations is defective or inadequate in some way.

Scientists themselves are most concerned with what they do in research. They tend to take the thought processes that drive their research for granted. Except for statistical testing, which is one component of assessment, these processes are less discussed than the results of scientific research. Most scientists learn the use of these thought processes indirectly by observing research progress. This book emphasizes the advantages of being explicit about those processes. Ecology is an interesting, but difficult, subject. Many of its valuable concepts either require many measurements to define them or can not be measured directly but are defined by theory. This book defines a method of reasoning for analyzing ecological concepts, how a new synthesis is made following research, and how that synthesis can be assessed.

1.4 Section I: Developing an analytical framework

Doing research is a different activity from learning by course work. This becomes apparent when research planning starts. Section I of this book provides answers to Questions 1–21 (Table 1.1) in the form of a description

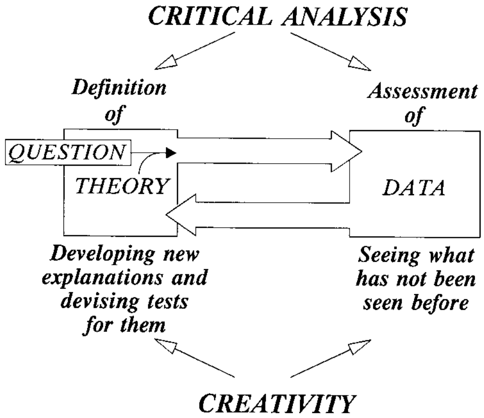

Fig. 1.2. Critical analysis and creativity must motivate the cycle of scientific advance. Critical analysis must ensure rigor in definition of problem, theory, and assessment of data. Creativity can occur during both theory definition and data analysis and is frequently stimulated by critical analysis.

of the process of research that can be followed, particularly at the planning stages when the task is analysis of the problem and how to solve it.

Chapter 2 discusses in detail Questions 1–21 (Table 1.1) as they relate to the five processes of research planning: (1) defining a research question; (2) applying creativity to develop new research ideas; (3) ensuring the proposed research has relevance to prior scientific knowledge; (4) ensuring the proposed research is technically feasible and can be completed with available resources; and (5) determining how conclusions can be drawn.

Chapter 3 details the key to research planning: making a conceptual and propositional analysis by defining three types of knowledge (Fig. 3.1): *axioms*, what we assume we know; *postulates*, what questions we have but stated in a propositional form so they can be classified as true or false using the research; and *data statements*, which define the data needed to classify the postulates as true, false, or acceptable with a certain probability. The hardest work can be in determining exactly what can be taken as an axiom and what must be researched as a postulate. The key to this is defining the individual concepts that make up axioms and postulates.

Chapter 4 illustrates conceptual and propositional analysis with an example, an investigation of the use made by small mammals of piles of woody debris cast up alongside a river after floods. Conceptual and propositional analysis is a progressive process that may take weeks or months to complete. This very active phase of research brings together published information in the scientific literature, information known about a field site or species, and knowledge of what can be done practically.

Chapter 5 presents a first discussion of the development and use of ecological theories to illustrate the importance of analysis. Though we continually seek generalities in our theories, we must modify them to investigate specific situations. Development of a theory to describe the post-glacial invasion of Alaska by tree species shows how both a theory, and the logic used to investigate it, can change. An investigation of interbreeding between related species of anadromous fish shows the difficulties in using a theory developed for one system as the basis for analyzing another one, even though the species are related.

Chapter 6 illustrates problems that can arise in making measurements and planning experiments. The properties of measurements to be made must be analyzed for their efficiency in representing the concept, their accuracy, and their precision. The example presented, concerning the control of photosynthesis rate of foliage on a mature *Pinus strobus* tree, illustrates how to proceed when encountering an unexpected result. It shows the importance of having competing postulates in research and of making more than one measurement of a new concept.

Chapter 7 introduces methods of reasoning used by scientists in their research and difficulties associated with them. Deduction and the rules of logic are descibed and the general inductive approach followed in research is illustrated. Conditions when it is possible to falsify a postulate are described, and why that can be an important procedure, and the logic for having competing postulates, rather than just one, is illustrated. In ecology we depend upon causal reasoning; different types of causes are illustrated.

Chapter 8 distinguishes between scientific and statistical inference. The tests and procedures that statistical science has produced are based on statistical theories whose assumptions must be understood before they can be applied. This is particularly important for ecological and environmental research, where some assumptions used in statistical theory may not hold in important ways. This chapter emphasizes the need for exploratory analysis to establish whether, and how, a statistical test can be constructed.

Chapter 9 concludes Section I by describing different individual scientific philosophies and how these influence research by motivating different types of analysis of scientific problems. Philosophies are neither right nor wrong, but are sets of ideas about how research is, or should be, conducted. A philosophy can bring both strengths and weaknesses to a research investigation. Some philosophies do make assumptions about the nature of what will be found out in ecology.

1.5 Section II: Making a synthesis for scientific inference

Ecology is characterized by use of concepts such as *ecosystem*, *community*, and *population* and properties such systems have such as *diversity*, *stability*, or *persistence*. These concepts can not be measured directly; we have to construct theory to define them. In Chapter 10 these are classified as *integrative* concepts and we build theory about them using both *functional* concepts, that define how organisms and the environment interact directly, and *natural* concepts, that define organisms and environmental factors or conditions. This classification acts as a heuristic for the development of ecological knowledge. We also have to recognize that our theories about *integrative* and *functional* concepts can take time to develop and, explicitly, that any theory may not be universally true. For example, a theory that explains high and low species diversity between examples of one type of ecosystem may not explain it between examples of another. We should not simply assume generality in the theories we propose. The idea that theories have domains of application is introduced in Chapter 10 and is used to illustrate how theories may develop and be reconciled with other, aparently conflicting, theories.

Ecological theories, particularly those defining integrative concepts, are complex and they can not be rejected by single, critical, investigations. We seek to know whether such theories are good explanations. In Section II a definition is made of what constitutes an explanation, and the idea of explanatory coherence for making an assessment is introduced; examples are given in each chapter of the section.

The use scientists make of ecological theory, and their concern about how to develop it, determine research strategy. Chapter 11 discusses some different research strategies described by philosophers who have studied science. They are used to illustrate what is critical in the different tasks of establishing a new theory and stimulating the development of a growing theory. The chapter discusses further applications of the conceptual classification given in this section and the development of explanatory coherence in different situations.

Difficulties in both the analysis of ecological systems, and the use of integrative concepts for making a synthesis, have led to the use of quantitative models. Chapter 12 illustrates assumptions of different types of model and discusses the difficulties those assumptions cause for using models to represent, or even replace, theory.

1.6 Section III: Working in the research community

In this book, attention is paid to the relationship between what we do as scientists and the social environment in which we work. A critical approach is the essential requirement for a research scientist; but this can be strongly influenced by colleagues, research sponsors, and sometimes environment and natural resources managers. Scientists must be aware of those influences and their consequences. Socially imposed restrictions on criticism and innovation can be the most difficult problem a young scientist encounters. This book stresses the need for scientists to develop the logical basis for their research and in this way to become an integral part of a community of scholars. Social and educational factors, however, can influence attempts to become part of a community.

Chapter 13 discusses the types of social influence in science and their effect on planning and conducting research and in preparing scientific papers for publication. The social difficulties that may be encountered in research are not simply something extra to be coped with. They are due to the very nature of research as an imprecise activity – where recent results are still insecure and we can not be certain of the best way ahead.

Chapter 14 illustrates particular difficulties faced by doing ecological research in an applied context where a natural resource is managed or impacts on people's economic or cultural well-being. Decisions about environmental policy and the management of natural resources are made from particular standpoints. Scientific research can influence these decisions but the ways this might occur most effectively still seem uncertain and can be influenced by the standpoints of scientists, managers, and policy-makers. Examples are given where scientific analysis was central to a particular resource management policy, and where it was excluded. In both cases major changes became inevitable: in the first as society's demands changed; in the second when environmental catastrophes occurred.

1.7 Section IV: Defining a methodology for ecological research

At appropriate points in the first three sections there are discussions of the strengths and weakness of well known techniques of investigation. A number of innovations are introduced for analyzing ecological research problems and making synthesis of results to develop new theory. Chapter 15 is an integrated description, presented as a methodology for ecological research, of *Progressive Synthesis*. This methodology has three principles:

> There should be continuous application of just and effective criticism.
> Precision is required in defining axioms and concepts, postulates and data statements, and theories.
> Explicit standards must be used to examine the relation between theory and data.

These principles are applied to a method for reasoning designed for making inference about ecological concepts and theories. This method focuses on how change can take place through concept definitions and the construction of theory, use of comparisons, and development and assessment of scientific explanations.

Chapter 16 reviews criticisms of ecological research: that there has been lack of progress, no general theory has emerged, ecological concepts are inadequate, and that ecologists fail to test their theories. These criticisms are based upon ideals about what types of knowledge we should be finding out in ecology and what are the most appropriate techniques of investigation. They have frequently been formed through observing sciences with different types of problem from those encountered in ecology. In contrast, Progressive Synthesis focuses on the method of reasoning that should be used in ecological research and how appropriate techniques of investigation can be applied.

1.8 Synopsis of methodological problems facing a new researcher in ecology

(1) Frequently the processes of scientific research are not made explicit to graduate students (Stock 1985, 1989). This book tackles this deficit directly by illustrating how to refine a question into a program of measurement and methods for making scientific inference.

(2) You have to master multiple processes to make progress in research. Simultaneously, you have to define what has been done, devise questions and research to answer them that will advance knowledge, construct investigations that will actually work, and most likely learn what procedures of statistical inference to use. This complete process of scientific research is difficult the first time you attempt it: as when riding a bicycle, you must learn to balance, watch the road ahead, and pedal, all at the same time. This book shows how to define a scientific objective, even for complex problems in ecology, and this provides direction that enables you to balance your different activities.

(3) As an undergraduate, you may have read original scientific papers and learned to debate opposing views. In research, you come closer to the center of discussion and debate, where opposing views have not been reconciled, and sometimes are not even fully defined, so no reconciliation may yet be possible. Then arguments are fierce, and social factors can play an important role in deciding who follows what argument. This book defines these issues to help you to identify the ideals that individuals and organizations may have and how those ideals may affect research objectives, methods, and interpretations.

(4) Ecology has some unique problems in the method of scientific reasoning for its important concepts. When ecologists express differences about the value of particular techniques of investigation they use, it is not always clear whether the resultant debates are about the scientific details or the philosophies behind their use of particular techniques. This book shows why different types of research problem require different techniques of investigation and presents a methodology for reasoning about ecological concepts and theories.

1.9 How to use this book to develop your research skills

The challenge of ecological research is not just in what you must learn but also in how you must think. The focus in this book is on developing a critical attitude about a scientific problem and constructing a procedure for assessment. The book will have the most practical value if you can follow four suggestions:

(1) *Adopt a scientific question you wish to investigate.* Establishing the logical basis for an investigation and determining what type of scientific inference should be made are best learned by applying the techniques of Section I to a real problem. Do not be concerned if your ideas are not yet crystal-clear – this book is designed for you! The techniques presented help to sharpen general ideas into specific research plans.
(2) *Practice the development of a "logic for discovery" with other students.* Set up small discussion groups with three or four other students working on similar research problems. It is most important to learn the art of criticism, particularly self-criticism, without being personally destructive either to your ideas or to those of others. It is essential to learn, in the planning stage, that an idea that you had was incomplete and to know what it feels like to improve that idea through further work, or to reject it and adopt another. You must learn how to treat an idea not as part of your own identity but as something to be turned over, poked at, and examined to see how it fits with other ideas.
(3) *Do not be apprehensive about, or dismissive of, philology or philosophy.* Philology is the science of language. Much science is about defining terms and much progress in ecology is made by developing definitions of concepts. Concepts start imprecise, become more precise as a research plan takes shape, and then sharpen even more by the end of the research. This process of definition and redefinition requires work – and extensive critical analysis. This book deliberately sets out to give you a framework for defining ideas, and deciding how certain you are about their definition. Words are all we have with which to express ideas in science. So being exact in science means being exact about how we define and use words. A philosophy is a system of thinking about things. We all have philosophies, though we may not think of them as such. The philosophy we hold can have a major influence on the way that we first cast a scientific problem – and it is frequently our philosophy that we have to question rigorously. This book examines different philosophies held by scientists and how they influence the approach to research.
(4) *Understand the strengths and weakness of science as a social activity.* Part of developing as a scientist is to associate with groups of people with interests in similar problems and frequently with similar approaches to solving them. For students starting research, "socialization" into a particular scientific group is very important if you are to absorb a

detailed understanding of problems and techniques. However, because the basis of good science requires developing a critical approach, you may sometimes find yourself challenging the very ideas, and ideals (philosophies), that the members of the group you have joined hold most dear.

1.10 Further reading

Mahoney (1976) gives a strong, and sometimes vehement, description of the logical difficulties of the scientific method and, particularly, scientists' failure to confront them. Stearns (1986, 1987) advises graduate students how to proceed in their research; Huey (1987) amplifies and debates that advice. The relationship between research student and supervisor is discussed in a publication of the Council of Graduate Schools (Anon. 1990), and lists of practical suggestions are given for both students and supervisor. Smith (1990) gives a guide for graduate students in the sciences to most practical things graduate students must do and be involved in and Locke *et al.* (1993) describe and analyze effective dissertation proposals.

The two questions ''How can we find things out?'' and ''How do we know whether our answers are correct?'' are the problems of developing a heuristic and an assessment procedure. Through his description of the types of theory constructed and whether, and on what grounds, they have been accepted, McIntosh (1980) shows how methodological problems associated with heuristics and assessment have been central to the development of ecology. His account is valuable as a background for understanding why some questions in ecology have been studied repeatedly and apparently not resolved.