

Scientific Method for Ecological Research

Scientists tend to take the thought processes that drive their research for granted, often learning them indirectly by observing first their supervisors and then their colleagues. This book emphasizes the advantages of being explicit about these thought processes and aims to help those undertaking ecological research to develop a critical attitude to approaching a scientific problem and constructing a procedure for assessment. The outcome is a text that provides a framework for understanding methodological issues and assists with the effective definition and planning of research. As such, it is a unique resource for anyone embarking on their research career. It also provides a valuable source of information for those more experienced researchers who are seeking to strengthen the methodology underlying their studies or who have an interest in the analysis of research methods in ecology.

DAVID FORD is a Professor in the College of Forest Resources at the University of Washington, USA. His teaching spans courses such as Scientific Method, Ecological Modeling, Spatial Processes in Ecology, and Ecology of Managed Forest Ecosystems.

Cambridge University Press
052166005X - Scientific Method for Ecological Research
E. David Ford
Frontmatter
[More information](#)

Scientific Method for Ecological Research

E. David Ford

College of Forest Resources, University of Washington



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
 052166005X - Scientific Method for Ecological Research
 E. David Ford
 Frontmatter
[More information](#)

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE

The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS

The Edinburgh Building, Cambridge CB2 2RU, UK

40 West 20th Street, New York, NY 10011-4211, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

Ruiz do Alarcón 13, 28014 Madrid, Spain

Dock House, The Waterfront, Cape Town 8001, South Africa

<http://www.cambridge.org>

© E. David Ford 2000

This book is in copyright. Subject to statutory exception
 and to the provisions of relevant collective licensing agreements,
 no reproduction of any part may take place without
 the written permission of Cambridge University Press.

First published 2000

Reprinted 2001, 2002

Printed in the United Kingdom at the University Press, Cambridge

Typeset in Garamond 11/13pt [vN]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing-in-Publication Data

Ford, E. D. (Edward David)

Scientific method for ecological research/E. David Ford.

p. cm.

Includes bibliographical references and indexes.

ISBN 0 521 66005 X (hardcover)

1. Ecology – Research – Methodology. 2. Science – Methodology.

I. Title.

QH541.2.F66 2000

577'.07'2 – dc21 99-30065 CIP

ISBN 0 521 66005 X hardback

ISBN 0 521 66973 1 paperback

Cambridge University Press
052166005X - Scientific Method for Ecological Research
E. David Ford
Frontmatter
[More information](#)

For Rosemary

Contents

Preface xv
Acknowledgements xviii

1	Component processes of ecological research	1
	Summary	1
1.1	Questions about the process of scientific research	2
1.2	Scientific methodology	4
1.3	Distinction between progress and process in scientific research	5
1.4	Section I: Developing an analytical framework	6
1.5	Section II: Making a synthesis for scientific inference	8
1.6	Section III: Working in the research community	9
1.7	Section IV: Defining a methodology for ecological research	10
1.8	Synopsis of methodological problems facing a new researcher in ecology	11
1.9	How to use this book to develop your research skills	11
1.10	Further reading	13
	Introduction to Section I: Developing an analytical framework	15
2	Five processes of research planning	19
	Summary	19
2.1	Introduction	20
2.2	Process 1: Defining a research question	21
2.2.1	Origins and types of research questions	21
2.2.2	Analysis of questions	24
2.3	Process 2: Applying creativity to develop new research ideas	28
2.4	Process 3: Ensuring the proposed research has relevance to prior scientific knowledge	29
2.5	Process 4: Ensuring the proposed research is technically feasible and can be completed with available resources	32
2.6	Process 5: Determining how conclusions can be drawn	33
2.6.1	Developing a data statement: An example	34
2.6.2	Using statistics to illuminate the problem, not support a position	38
2.7	Further reading	40

3	Conceptual and propositional analysis for defining research problems	41
	Summary	41
3.1	Introduction	41
3.2	Constituents and properties of theories	42
3.3	Conceptual and propositional analysis	56
3.3.1	Phase One: Identifying the principal issues	57
3.3.2	Phase Two: Classifying concepts according to their status in the progress of research	58
3.3.3	Phase Three: Examining the complete research procedure	65
3.4	Representing theories as networks	65
3.5	What can be gained from a conceptual and propositional analysis?	67
3.5.1	Deciding whether you can assume something or must investigate it	69
3.5.2	Understanding logical relationships between different pieces of knowledge	69
3.5.3	Assessing how complete a theory is	70
3.5.4	Knowing when to start practical investigation	70
3.6	Conclusion	71
3.7	Further reading	71
4	Development of a research plan	73
	Summary	73
4.1	Introduction	73
4.2	Process 1: Defining a research question	74
4.2.1	The first description	74
4.2.2	Initial development of a theory for the problem	76
4.2.3	First definitions	77
4.2.4	First consideration of Process 4: Ensuring the proposed research is technically feasible and can be completed with available resources	78
4.2.5	First consideration of Process 2: Applying creativity to develop new research ideas	79
4.2.6	Continuation of Process 1: Defining a research question	80
4.3	Process 4: Ensuring the proposed research is technically feasible and can be completed with available resources	85
4.4	Process 3: Ensuring the proposed research has relevance to prior scientific knowledge	93
4.5	Process 2: Applying creativity to develop new research ideas	94
4.6	Process 5: Determining how conclusions can be drawn	95
4.7	Steel's comments on the planning process after completing her Master's thesis	101
4.8	Further reading	102

CONTENTS

ix

5	How theories develop and how to use them	103
	Summary	103
5.1	Introduction	103
5.2	Development of a theory from a simple postulate: Late-Quaternary vegetation change in central Alaska	108
5.2.1	Stage 1: Rejecting a simple postulate	108
5.2.2	Stage 2: Exploring for spatial and temporal changes	111
5.2.3	Stage 3: Introducing axioms from tree ecology	113
5.2.4	Stage 4: Increasing the precision of the theory	114
5.2.5	Stage 5: Working towards explanations that are coherent with meteorological theories	115
5.2.6	Assessment of theory development	116
5.3	Practical application of a theory: Hybridization in fish species	118
5.4	Development, properties, and use of ecological theories	127
5.5	Further reading	129
6	The art of measurement and experiment	131
	Summary	131
6.1	Introduction	131
6.2	Principles of measurement for new concepts	133
6.3	Experimental analysis of ecological systems	136
6.4	Planning an analytical experiment: An example – control of photosynthesis rate of <i>Pinus strobus</i> trees	142
6.4.1	Results from an improved measurement technique	142
6.4.2	Observing an anomaly	143
6.4.3	Making a conceptual analysis of the problem	146
6.4.4	Constructing multiple postulates	149
6.4.5	Choosing a postulate to study	152
6.4.6	Defining the experimental conditions	156
6.4.7	Developing a measurement	158
6.4.8	Designing treatment application, replication, and controls	159
6.4.9	Investigating ancillary processes to aid interpretation and assessment	164
6.5	Whole-system analytical experiments	164
6.6	Discussion	165
6.7	Further reading	167
7	Methods of reasoning in research	169
	Summary	169
7.1	Introduction	170
7.2	Principles of propositional logic	171
7.3	The use of propositional logic in ecological research	178
7.4	The hypothetico-deductive method and use of falsification in scientific reasoning	183
7.5	An exercise in choosing between postulates expected to be true and postulates expected to be false	187
7.6	How to decide whether to attempt confirmation or falsification	189

7.7	Using contrasts	195
7.8	Causality	196
7.9	A strategy for constructing theory using multiple working postulates	200
7.10	Discussion	201
7.11	Further reading	202
8	Assessment of postulates	203
	Summary	203
8.1	Introduction	204
8.2	Refining postulates using exploratory analysis	206
8.3	Developing a scientific procedure and set of measurements	210
8.4	Satisfying the logic required for statistical inference	219
8.4.1	Constructing and assessing a statistical hypothesis	226
8.4.2	Completing the data statement	231
8.5	Discussion	231
8.6	Further reading	234
9	Individual philosophies and their methods	235
	Summary	235
9.1	Introduction	235
9.2	Initial assumptions	239
9.2.1	Teleology	239
9.2.2	Parsimony	242
9.2.3	Holism and reductionism	243
9.2.4	Teleology, parsimony, and reductionism in ecology	244
9.3	First formalizations of methodology	251
9.3.1	Empiricism	251
9.3.2	Rationalism	254
9.3.3	Empiricism and rationalism in ecology	256
9.4	Uncertainty about the objectivity of method	264
9.4.1	Criticism	264
9.4.2	Relativism	265
9.4.3	Statistical experimentalism	266
9.5	Discussion	267
9.6	Further reading	268
	Introduction to Section II: Making a synthesis for scientific inference	269
10	Properties and domains of ecological concepts	279
	Summary	279
10.1	Introduction	280
10.2	Definition and purpose of ecological concepts	281
10.3	The domain of functional and integrative concepts	288
10.4	Example of use and development of ecological concepts and their domains	291

CONTENTS

xi

10.4.1	Developing definitions of natural and functional concepts	291
10.4.2	Using functional concepts to define an integrative concept	293
10.4.3	Making inference about an integrative concept	300
10.5	Discussion	305
10.6	Further reading	308
11	Strategies of scientific research in ecology	309
	Summary	309
11.1	Introduction	310
11.2	Does ecological science advance through recurring revolutions?	311
11.2.1	The ecosystem revolution	313
11.2.2	The progress of normal science	315
11.2.3	Did a revolution terminate the paradigm?	319
11.2.4	How useful is Kuhn's theory for understanding research strategy?	323
11.2.5	Scientific inference and the ecosystem paradigm	324
11.3	The methodology of scientific research programs	327
11.3.1	A strategy for continuous assessment	327
11.3.2	The components of a scientific research program	328
11.3.3	Top-down and bottom-up forces in population and community ecology	330
11.3.4	Criticisms of the methodology of scientific research programs	342
11.4	The investigation of domains	344
11.5	Discussion	348
11.6	Further reading	349
12	Use of mathematical models for constructing explanations in ecology	351
	Summary	351
12.1	Introduction	352
12.2	Dynamic systems models	353
12.2.1	Simple differential equation models	353
12.2.2	Using dynamic systems models to predict the unexpected	359
12.2.3	Fitting dynamic systems models to ecological systems	363
12.3	Statistical models of dependence	368
12.3.1	Modeling dependence in time series as a stochastic process	369
12.3.2	Assessing a stochastic time series model as an explanation	375
12.4	Systems simulation models	378
12.4.1	Objectives, theory, and model design	379
12.4.2	Calibration and validation	382
12.4.3	Assessing using multiple outputs	385
12.5	Discussion	389
12.6	Further reading	391

Introduction to Section III: Working in the research community	393
13 Scientific research as a social process	395
Summary	395
13.1 Introduction	396
13.2 Social influences and social structures	397
13.2.1 The balance between norms and counternorms in scientists' behavior	397
13.2.2 Cooperation and competition between individual scientists	403
13.2.3 Fraud and misconduct in science	407
13.2.4 The role of gender in scientific debate and discovery	410
13.3 Creation and use of scientific literature	412
13.3.1 Constructing a scientific paper	413
13.3.2 Peer review	415
13.3.3 Problems of quantity and quality	421
13.3.4 Literature citation and its analysis	423
13.4 Developing and using explicit standards of criticism to construct objective knowledge	425
13.5 Discussion	427
13.6 Further reading	429
14 Values and standpoints and their influence on research	431
Summary	431
14.1 Introduction	431
14.2 Standpoints in science, management, and policy	433
14.2.1 Scientists' standpoints	433
14.2.2 Managerial standpoints	439
14.3 Reviewing and funding scientific research	443
14.3.1 Research proposals and their peer review	444
14.3.2 Scientific research with policy implications	452
14.4 Science, scientists, and society	455
14.5 Discussion	462
14.6 Further reading	463
Introduction to Section IV: Defining a methodology for ecological research	465
15 The methodology of progressive synthesis	467
Summary	467
15.1 Introduction	468
15.2 The standpoint of Progressive Synthesis	468
15.2.1 Types of acceptable explanation	469
15.2.2 Certainty in scientific inference	472
15.3 Principles of Progressive Synthesis	474

CONTENTS

xiii

15.3.1	Principle I: Continuous application of just and effective criticism	475
15.3.2	Principle II: Precision is required in defining axioms and concepts, postulates and data statements, and theories	476
15.3.3	Principle III: Explicit standards must be used to examine the relation between theory and data	478
15.4	Components of the method of Progressive Synthesis	481
15.4.1	Component 1: Analyze the question and seek to use contrastive techniques to focus the research	482
15.4.2	Component 2: Expect to use different techniques of investigation as theories develop and new types of question are asked	487
15.4.3	Component 3: Refine both measurement and concept definitions	488
15.4.4	Component 4: Specify the new synthesis resulting from the research	488
15.4.5	Component 5: Define explanatory coherence of the synthesis to make a scientific inference	493
15.5	Discussion	494
15.6	Further reading	496
16	Criticisms and improvements for the scientific method in ecology	497
	Summary	497
16.1	Introduction	497
16.2	Criticisms of ecological research	499
16.2.1	There has been lack of progress in ecology	499
16.2.2	No general theory has emerged	500
16.2.3	Ecological concepts are inadequate	503
16.2.4	Ecologists fail to test their theories	505
16.3	Suggestions made for improving ecological research	506
16.3.1	Suitable research objectives for ecology	507
16.3.2	Forms of reasoning that should be used	511
16.3.3	The relation between concepts and theories	511
16.4	Ideals and strategy of Progressive Synthesis	514
16.5	Further reading	518
	<i>Appendix: Suggestions for instructors</i>	521
	<i>References</i>	525
	<i>Glossary</i>	541
	<i>Author index</i>	555
	<i>Subject index</i>	559

Preface

My motivation for writing this book was to provide a text for new researchers in ecology, giving a framework for understanding methodological issues, and helping them to define and plan research. In the late 1980s I started teaching a graduate course in research methods at the University of Washington. My faculty colleagues were concerned that students were having difficulty writing research plans. At the same time statistical consultants were spending much time asking students to clarify their study objectives and logic of investigation before statistical advice could be given. Discussions with colleagues at other universities suggested that these were not unusual circumstances.

Problems with ecology and its methods are also encountered by established researchers and there have been substantial criticisms of the subject and its research methods. Concern has been expressed that there has been a lack of progress in ecology, that no general theory has emerged, that ecological concepts are inadequate, and that ecologists fail to test their theories (Chapter 16). While some of this criticism may be justified, the students' needs required me to look beyond it and seek ways of being constructive. This has required making two distinctions that are fundamental to the way this book is written.

The first distinction is between methods of *reasoning* such as how we use logic, construct a hypothesis and develop a theory, and techniques of *investigation*, such as an experiment, or a survey, or constructing a simulation model. Much of this book is about methods of reasoning for ecological research and how they can best be used with particular techniques of investigation. Analysis of methods of reasoning leads to answers to the question "How can we make scientific inference in ecology?" Ecologists have tended to define and answer this question in terms of what they actually do in their work rather than the processes of reasoning they use.

The second distinction is between different types of concept we use in ecology. For some concepts we make measurements or observations but others can be defined only through abstract reasoning in the process of theory construction. Difficulties with this latter type of concept arise in even the most practical problems. For example, I have taught a number of students involved in *restoration* ecology, sometimes applied to *wetlands*. Neither of

these concepts have definitions that are simple, general and easy to apply consistently to all particular cases. Government agencies who want *restoration* may fund research to show how it could be done, but may not define precisely what is required, or may define only certain aspects. Researchers writing grant or contract proposals for this work must communicate with these agencies on the agencies' own terms and may set practical objectives and suggest methods that are considered to be successful in other circumstances. Difficulties in defining precisely what would constitute *restoration* of a different *wetland* in new particular instances may become apparent only during detailed research planning.

It is because of our difficulties with definitions, and so with the relationship between general ecological theory and particular instances, that we have to be precise about the methods of reasoning we use and how we make scientific inference. Some ecologists have taken refuge from difficulties about method by emphasizing the values of particular techniques of investigation, e.g., experiments are the key to successful research because they can be used to test hypotheses, or in criteria about data, e.g., questions must be asked that can be answered with a significant *P* value. Such emphases and repeated application of a particular research technique or approach can be a solution for the individual scientist working in an established research program (see Chapter 11). But they imply that only certain types of question can be tackled. Faced with a class of graduate students, all with interesting but different types of research, I found a more comprehensive approach was necessary.

This book deals first with problems as they are most usually encountered by beginning researchers and then progresses to wider issues in ecological research and the consequences of social systems on the research process. Section I presents techniques for conceptual and propositional analysis that can be used to define a research question, develop statements defining the investigations to be made, and specify how they will answer the question. Section I defines different properties that measurements can have and describes the range of experiments used in ecology and the types of question for which they are appropriate. Section I also defines the types of logic that scientists use, particularly when falsification is possible, the importance of causal arguments, and why contrasts are so important. The requirement for exploratory work to define an effective statistical hypothesis test is described and the distinction is made between statistical and scientific inference.

Research planning starts with analysis but it must also incorporate how a comprehensive assessment will be made of work to be done. This leads to Section II and defining scientific inference, particularly for the types of concept we use in ecology. The approach taken uses work from the philosophy of science that has focused on defining scientific explanation and its assessment through developing explanatory coherence. Section II describes

how scientific inference is developed and refined by groups of scientists working in research programs.

This book defines a methodology for ecological research in terms of methods of reasoning and principles for applying them. The essential principle is continuous application of *just and effective criticism*. A consequence of depending upon criticism is that explicit account must be taken of social processes in research. These are discussed in Section III. Social studies of the research process have advanced remarkably but scientists are sometimes impatient with social analysis of their subject, or even angered if studies suggest that what may actually be going on does not meet their ideal. But the consequences of these findings, and the details they describe, illustrate how difficult it can be to achieve just and effective criticism. Because we depend upon abstract reasoning in ecology and can not assume that scientific questions can be resolved in a straightforward way by measurement, then we must be explicit about use of criticism. The result of Section III is a four-stage definition of the process of criticism.

Some experienced researchers have little patience with making a formal description of the research process, believing strongly that research is best taught by the student taking the role of apprentice in following their procedures and methods. After long practice, experienced researchers may find the logic of what to do next obvious and attempts to take a cautious and refining view of all the arguments can seem a waste of time, pedantic, or even threatening. However, when you are at the outset of research, some of the assumptions made by established researchers are not obvious and the process described here can be helpful. This book does not suggest that the close relationship between supervisor and student can be replaced. Far from it. Such a relationship is essential. However, it is important to be explicit about the difficulties that we all can have with ecological research.

In addition to being a text for new researchers this book, I hope, provides a reference for definitions of terms and components of the debate over method in ecology. As a subject develops and encounters new types of problem so too must its methods evolve. Some critics of ecology have been led by their criticism to suggest restrictions either in what the aims of the subject should be or in the techniques of investigation that should be used. The methodology of *Progressive Synthesis*, defined in Chapter 15, is not restrictive in either of these ways. However, it does require that researchers be explicit in how they define scientific inference and that they analyze carefully their ideals for what research should achieve and how those ideals influence research.

Acknowledgements

I am grateful to successive classes of students taking the course QERM521, whose diverse research problems have repeatedly challenged my ideas about ecological research. My special thanks are due to Ashley Steel and Denise Hawkins, who, when they were graduate students, allowed me access to their first thoughts about a research problem and have permitted me to publish these ideas and their development. This is courageous of them. As discussed in the book, the scientific world has conventions about how research must be presented that are not designed to illustrate how ideas develop. I am also grateful to Linda Brubaker, Bob Teskey, and David Janos for painstaking reviews of the use I made of their work, to Bruce Menge, Stephen Carpenter, and Bob Paine for helpful insights into the progress of their research, and Joshua Klayman and Paul Thagard for valuable comments on the use I made of their approaches to the analysis of science and its methods.

I particularly wish to thank David Chart of the Department of History and Philosophy of Science, Cambridge University, for his review of my use of ideas from philosophy of science. His detailed comments were always sympathetic to the purpose of the book and I hope my responses are adequate.

I am indebted to Carol Perry, both for her book on technical writing (Perry 1991), and for her extensive and repeated editing of Section I. Writing about how we can analyze problems is challenging and she consistently persuaded me towards accessible text.

I am most appreciative to colleagues at the University of Washington: to Bob Francis, John Skalski, and Bob Stickney for initial ideas and encouragement; to Jim Agee, Bob Edmonds, Tom Hinckley, Dave Petersen, Joel Reynolds, and Doug Sprugel for ideas and motivating comments; and to Ray Hilborn and Walt Dickoff for their positive and constructive comments during peer review. I wish to thank Peter Guttorp and the National Center for Research in Statistics and the Environment for support in writing Chapter 12.

Foundation work was done during a sabbatical at Harvard University and the University of Lancaster. I am grateful to David Foster and Peter Diggle, respectively, for their hospitality and to Harvard University for a Bullard Fellowship whilst I was there. At Harvard a reading group of Emery Boose,

Jana Compton, David Janos, and Jason McLachlan kindly commented on the text. I am particularly grateful to Sally Hollis for her comments and suggestions on Chapter 8.

My thanks are due to Alan Crowden of Cambridge University Press for his perseverance, support at crucial times, and arranging for critical reviews, particular by Craig Loehle, who made many helpful suggestions, and two anonymous referees.

The support, encouragement, and tolerance of my wife Rosemary have been selfless and given so willingly and freely.