Real World Ecology

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Editors

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Large-Scale and Long-Term Case Studies and Methods

Foreword by Stephen R. Carpenter

Springer

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To our mothers, whose love and support
we appreciate.

Foreword

Ecology is not rocket science – it is far more difficult (Hilborn and Ludwig 1993). The most intellectually exciting ecological questions, and the ones most important to sustaining humans on the planet, address the dynamics of large, spatially heterogeneous systems over long periods of time. Moreover, the relevant systems are self-organizing, so simple notions of cause and effect do not apply (Levin 1998). Learning about such systems is among the hardest problems in science, and perhaps the most important problem for sustaining civilization. Ecologists have addressed this challenge by synthesis of information flowing from multiple sources or approaches (Pickett et al. 2007). Some major approaches in ecology are theoretical concepts expressed in models, long-term observations, comparisons across contrasting systems, and experiments (Carpenter 1998). These approaches have complementary strengths and limitations, so findings that are consistent among all of these approaches are likely to be most robust.

Ecosystem data are noisy. There are multiple sources of variability, such as external forcing, endogenous dynamics, and our imperfect observations. Thus it is not surprising that statistics have played a central role in ecological inference. However, with few exceptions the statistical approaches available to ecologists have been imported from other disciplines and were designed for problems that are simpler than the ones that ecologists face routinely. If you need to cut a board and all you have is a hammer, you might try pounding on the board until it breaks. Such a misapplication of force resembles some uses of statistics in ecology. But the metaphor is not quite right. It would be more accurate to say that ecosystem and landscape ecologists need to create and compare multifaceted models for large-scale processes, whereas the readily available tools were designed for testing null models that are usually trivial or irrelevant for this family of ecological questions.

The mismatch between the needs of scientists and the availability of statistical tools is acute in the analysis of ecosystem experiments. Ecosystem experiments have been an important contributor to ecological science for more than 50 years (Likens 1985, Carpenter et al. 1995). While humans have manipulated ecosystems since at least the beginnings of agriculture, if not longer, deliberate experiments for learning about ecosystems are traced to limnology in the 1940s (Likens 1985). The earliest whole-lake manipulations lacked reference systems, and so sometimes it was difficult to determine whether changes in the ecosystems were caused by the manipulations or by other environmental factors. In 1951, Arthur Hasler and his students divided an hour-glass shaped lake with an earthen dam, thereby creating two basins, Paul and Peter lakes. Peter Lake was manipulated, while Paul Lake served as an unmanipulated reference ecosystem (Johnson and Hasler 1954). The use of a reference or "control" ecosystem was a pathbreaking innovation (Likens 1985). It allowed Hasler and his students to separate the effects of the manipulations of Peter Lake from those of the environmental variability that affected both lakes (Stross and Hasler 1960, Stross et al. 1961). As a result of their experiences as students of Hasler, Gene Likens and Waldo Johnson were inspired to create two of the most influential centers of ecosystem experimentation in the world, the Hubbard Brook Ecosystem Study (Likens 2004) and the Experimental Lakes Area (Johnson and Vallentyne 1971).

Most ecosystem experiments involve spatially extensive systems (often observed at several spatial extents) over long time spans. Such experiments pose statistical challenges that cannot be handled by the methods of laboratory science or small agricultural plots (Carpenter 1998). It is not possible to substitute small-scale experiments run for short periods of time, because results of such experiments do not predict dynamics at spatial and temporal scales relevant to ecosystem science or to management (Carpenter 1996, Schindler 1998, Pace 2001). Instead, we must perform our studies at the appropriate scales – possibly at multiple scales. Then, we must learn how to learn from noisy observations of transient, heterogeneous, and non-replicable systems. This is a daunting challenge.

Thus many ecologists have broken free of the constraints of older statistical methods in order to explore new alternatives that seem better-adapted to the world of large-scale ecological change. The method of multiple working hypotheses (Chamberlain 1890) is now explicit in many ecological papers. Multiple hypotheses are expressed as quantitative models and confronted with data (Burnham and Anderson 1998, Hilborn and Mangel 1997). New approaches are explored for long-term monitoring data (Stow et al. 1998). Experiments are designed for critical tests of multiple alternative models to address fundamental questions about ecological dynamics (Dennis et al. 2001, Wootton 2004). Comparisons of multiple models are providing new insights about long-term field observations of big systems (Ives et al. 2008). These are but a few selections from a diverse and rapidly growing literature. This new phase of ecological research is turbulent and subject to rapid intellectual progress. Some of the emerging practices are nonstandard and are themselves objects of inquiry. Some approaches are tried, found wanting, and abandoned. New approaches are introduced frequently. It is an era of creativity, innovation, discarding of mistakes, and selection among alternatives – in a nutshell, a time of rapid evolution by the discipline.

The volume before you presents a sampling of case studies and syntheses from this fertile field of research. The authors and editors aim to improve our tools for ecological inference at scales that are relevant for fundamental understanding, as well as for management of ecosystems and landscapes. The book conveys the excitement and novelty of emerging approaches for learning about large-scale ecological changes.

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Chapter 1
Introduction – Unprecedented Challenges in Ecological Research: Past and Present

ShiLi Miao, Susan Carstenn and Martha Nungesser

1.1 Unprecedented Challenges in Ecological Research

The focus of ecological research has been changing in fundamental ways as the need for humanity to address large-scale environmental perturbations and global crises increasingly places ecologists in the limelight. Ecologists are asked to explain and help mitigate effects from local to global scale issues, such as climate change, wetlands loss, hurricane devastation, deforestation, and land degradation. The traditional focus of ecology as "the study of the causes of patterns in nature" (e.g., Tilman 1987) has shifted to a new era in which ecological science must play a greatly expanded role in improving the human condition by addressing the sustainability and resilience of socio-ecological systems (Millennium Ecosystem Assessment 2003, Palmer et al. 2004). In the twenty-first century, scientists studying ecological science are required not only to understand mechanisms of ecosystem change and develop new ecological theories but also to contribute to a future in which natural and human systems can coexist sustainably on the Earth (Carpenter and Turner 1998, Hassett et al. 2005). This unprecedented challenge demands that ecologists link science to planning, decision- and policy-making, forecasting ecosystem states, and evaluating ecosystem services and natural capital (Carpenter et al. 1998, Clark et al. 2001b). To realize these goals, ecologists must expand temporal and spatial scales of research, develop novel design approaches and analytical tools that meet the demands of this increasingly complex milieu, and provide education and training in using these tools.

Ecological research began with observational field studies, then moved to experimentation, at which time the difficulty of isolating and controlling the variables that influence ecosystems became apparent (McIntosh 1985). In response, ecologists tried to reproduce systems on a smaller spatial scale using microcosms and mesocosms, where the influence of variables could be systematically isolated, controlled, and tested (Forbes 1887, Beyers 1963, Hutchinson

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1964, Abbott 1966, 1967). Emphases on whole ecosystem studies followed Tansley (1935) and H.T. Odum and E. P. Odum's ecosystem concepts (Odum and Odum 1955, Odum 1955) have been pursued for over half a century by ecologists working in a wide array of ecosystems including forests (Edmisten 1970, Likens et al. 1970, Beier and Rasmussen 1994), lakes (Schindler 1971, 1973, Carpenter 1996, Vitousek et al. 1997, Carpenter 1998, Lamon III et al. 1998), deserts (Schlesinger 1990, Havstad et al. 2006), grasslands (Risser and Parton 1982, McNaughton and Chapin 1985), estuaries (Martin et al. 1990, Martin et al. 1994), and wetlands (Odum et al. 1977, Woodwell 1979, Likens 1985, Niswander and Mitsch 1995, Mitsch et al. 1998). From the persistent efforts of ecologists, including ecosystem and landscape ecologists, ecosystem science has developed into a well-established and diverse discipline that bridges the gap between fundamental research and applied problem solving (Carpenter and Turner 1998, Schindler 1998, Turner 2005). However, these and other studies collectively revealed critical issues for the advancement of ecology: multiple scales of spatial and temporal extent and variability, complex interactions, and system feedbacks.

Ecologists must now reach beyond focusing on simple systems with few variables to addressing complex ecosystems and landscapes with many uncontrolled variables operating across multiple spatial and temporal scales (Carpenter 1996, Peters et al. 2008). Conceptually, these ideas are illustrated in Fig. 1.1. Traditional ecological studies have focused largely on small-scale, short-term questions that can be addressed by replicated designs and statistical null hypothesis testing. Statistical tools for these questions are well understood and widely applied. These studies have tried to define causal relationships and develop ecological theories that lead to greater understanding of natural systems. The applicability of these approaches to provide greater understanding is limited by space, time, complexity, and the ability to replicate the study sites. However, many of the statistical techniques (in the toolbox on the left, Fig. 1.1) used to design and analyze these studies are not transferable to large-scale ecological research, as it generally encompasses large spatial scales, long temporal scales, and high complexity including feedbacks and nonlinear dynamics resulting in statistical uncertainty. New tools have been and continue to be developed to address the demands for analytical procedures that support predictions of future ecological conditions, policy development, environmental management and sustainability, and assessing environmental impacts, but refinement is needed for both experimental design and analysis.

To some ecologists, it has become apparent that many classical statistical approaches developed in other fields, such as randomized block design and analysis of variance, no longer fit the scope and objectives of large-scale and long-term ecosystem and landscape studies (Carpenter 1998, Grace et al. Chapters 2 and 11, Canham and Pace Chapter 8). Increasingly, ecologists question the appropriateness of null hypothesis testing in impact assessment and ecosystem restoration (Carpenter 1998, Green et al. 2005, Stephens et al. 2006). There is an

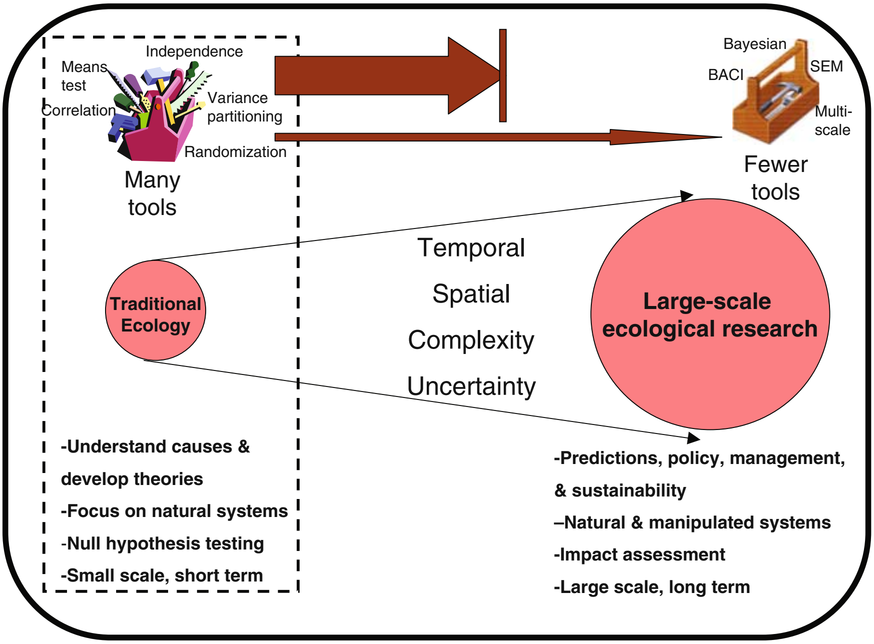

Fig. 1.1 We propose a modified paradigm for ecology that encompasses a much broader physical and temporal scale than traditionally taught ecology, requiring a very different approach to analysis and design of experiments. The approach is similar to that of the Gordian knot, known in mythology as a seemingly intractable problem that can be solved by a bold stroke. The problems addressed are those involving management, sustainability, policy, impact assessment, and predictions based upon issues that encompass large spatial scales, long temporal scales, complexity, and uncertainty that render traditional, null hypothesis based studies irrelevant. New experimental designs and analytical tools are required to address these questions. Traditional ecology, in contrast, focuses on smaller-scale, short-term questions that can be addressed by replicated designs and statistics that test a null hypothesis. Statistical tools for these questions are well understood and widely addressed, and while some may be applicable to these non-traditional approaches, most are generally inappropriate for these complex and difficult ecological questions

increasing call for a paradigm shift in statistical methodology (McBride et al. 1993, Maurer 1998, Germano 1999, Johnson 1999, Anderson et al. 2000, McBride 2002), and leadership is urgently needed to ask appropriate questions, design better studies, and develop analytical practices for ecological research in today's world.

In this volume, we offer our experience in design and analysis to meet the challenges and find solutions to large-scale and long-term ecological research issues. In each case study, alternative designs and/or analytical approaches are applied to research where replication was not practical, incorporating temporal and spatial scaling, and other challenges of non-traditional research (Table 1.1).

Table 1.1 Highlights of nine case-study chapters including ecological issues, systems, scales, and their design and analytical features

								Analytical approach	
Chapter	Authors	Ecological issues	Systems	Scales	Response variables or Parameters	Disturbance	Design or Statistical issue	Statistical modeling	Conceptual or Empirical modeling
2	Grace & Youngblood	Fire & forest management	Forest	Multiple spatial	Vegetation & pine bark beetle	Pulse	Partitioning variance vs ecological understanding	Structural equation modelling	
3	Peters et al.	Regime shift grassland to shrublands	Grassland	Cross-scale	Native plant cover, density, & spatial distribution	Press	Cross-scale design	Quantile regression	Simulation, Cellular automata
4	Miao et al.	Fire & ecosystem restoration	Wetland	Multiple temporal & spatial	Water, soil, & vegetation total phosphorus	Pulse; Press	Multiple-scale design & asymmetric sampling scheme	Moving regression vs. ANOVA	
5	Stow et al.	Ecosystem management	Lake	Multiple temporal & spatial	Water column chlorophylla & total phosphorus	Press	Multi-level, cross-system inference & prediction	Bayesian hierarchical models	
6	Fortin & Melles	Avian response to forest loss	Forest	Large-scale pattern	Ovenbird	Press	Interplay of data acquisition, resolution & spatial structure scales	Univariate	

Table 1.1 (continued)

								Analytical approach	
Chapter	Authors	Ecological issues	Systems	Scales	Response variables or Parameters	Disturbance	Design or Statistical issue	Statistical modeling	Conceptual or Empirical modeling
7	McGowan & Leavitt	Climate change, fisheries, & lake management	Lake	Multiple temporal & spatial	Sediments, isotopes, pigments, water, quality, & salmon	Multiple	Retrospective analysis	Synchrony, variance partitioning, time series, & correlations	explicit spatial contrasts
8	Canham & Pace	Watershed nutrient loading	Watersheds & Lake	Linkages between scales	Chemical constituents	Press	Identifying model parameters	Spatial regression	Empirical
9	Tian et al.	Human-induced changes & Scaling	Forest, grassland, cropland	Regional (US & China)	Carbon storage & flux	Press	Extrapolation; assessment; prediction		Integrated regional modelling
10	Luo & Hui	Climate Change	Telexstrial Ecosystem	Multiple	Photosynthesis; C partitioning & respiration	Step v. Gradual	Prediction		Inverse analysis

1.2 Major Developments of Alternative Experimental Designs

The evolution of alternative design approaches started in the middle of the twentieth century and continues today. Non-replicated experimental design, such as paired treatment and control or reference, dates back to 1948, when Hasler and his colleagues (Hasler et al. 1951) experimented with two lakes in Chippewa County, Wisconsin; one lake was experimentally manipulated (limed) and the other served as a control or reference. The paired treatment–control design was applied by Likens and his colleagues to study forested ecosystem processes and associated aquatic ecosystems on a watershed scale at the Hubbard Brook Experimental Forest in New Hampshire (Bormann et al. 1968, Likens 1985 and references therein). Later, Box and Tiao (1965, 1975b) developed the Before–After (BA) design to assess the effects of new environmental laws and a new freeway on Los Angeles air-pollution levels, after which it was applied to other air pollution studies (Hilborn and Walters 1981, Morrisey 1993). The BA design has no "control," therefore it cannot eliminate the possibility that an effect may have resulted from something other than the studied impacts or treatments. To address this shortcoming, Green (1979) recommended sampling both an impact and a control site before and after a disturbance, i.e., Before–After-Control-Impact (BACI), as an appropriate design for environmental assessment, emphasizing the necessity of the control site.

Some approaches to BACI were criticized by Hurlbert (1984) because of potential problems in statistical inference arising from the lack of independent replicates, both spatial and temporal, which was termed "pseudoreplication." Though Hurlbert's argument was countered for the specific issue of "pseudoreplication in time" (Stewart-Oaten et al. 1986), the central premise of the paper stimulated a discussion among ecologists, statisticians, and editors of ecological journals that has highlighted limitations in both classical statistical inference and ecological experimentation (Carpenter 1990, Hargrove and Pickering 1992, Carpenter 1996).

Furthermore, some scientists developed the Before–After-Control-Impact Paired Series design (BACIPS), which estimates not only the spatial variability of data collected from a treatment and control but also the temporal variability of the data (Bernstein and Zalinski 1983, Stewart-Oaten et al. 1986). The BACIPS design was further developed through theoretical and practical applications and summarized in a book edited by Osenberg and Schmitt (1996) and in a monograph by Stewart-Oaten and Bence (2001). In spite of continued improvements, the BACIPS design has not been enthusiastically received. One reason hindering BACIPS wide-scale acceptance and application is that it requires extensive sampling both before and after the treatment or impact, and often these data are not available. Nonetheless, various modified non-replicated designs have continued to emerge including Beyond BACI (Underwood 1992, 1993, 1994) and multiple BACI (MBACI) (Keough and Quinn 2000). In an attempt to increase statistical rigor, the Beyond BACI design employs multiple randomly selected control locations, and the MBACI design includes both multiple controls and multiple treatment sites. Non-replicated designs have received limited acceptance for environmental monitoring and are virtually ignored by scientists in experimental ecological fields.

The BACI design and its more recent modifications have considerably improved the power and sensitivity of statistical procedures to detect impacts by minimizing the confounding effects imparted by natural variation and factors other than experimental manipulation. This design has been used in both the design of environmental assessments (Stewart-Oaten et al. 1992) and ecosystem evaluation studies (Anderson and Dugger 1998). For example, the largest river restoration project in the world, Florida's Kissimmee River Restoration Project, incorporates ecological monitoring studies that use BACI- and BACIPS-like sampling designs to evaluate restoration success (Bousquin et al. 2005).

More recently, Legendre et al. (2002) considered whether spatial autocorrelation effects could be eliminated by varying the design of field surveys and by conducting stochastic simulations to evaluate which design provides the greatest statistical power. In addition, multi-scale experimental designs have emerged as a powerful tool for identifying the mechanisms underlying ecosystem change. Ellis and Schneider (1997) integrated Control/Impact (CI) and BACI designs along an environmental gradient to detect the spatial extent and varying magnitude of environmental impacts. Petersen et al. (2003) proposed multi-scale experiments in coastal ecosystems. Peters et al. (Chapter 3) applied a design incorporating multiple interacting scales to assess pattern and mechanisms of woody species encroachment into grasslands, and Miao et al. (Chapter 4) applied MBACI designs to assess ecological impacts of repeated fires on wetland ecosystem restoration. Moreover, Barnett and Stohlgren (2003) and Hewitt et al. (2007) demonstrated the effectiveness and required spatial extent of a monitoring program by applying a multi-scale nested sampling design to assess local and landscape-scale heterogeneity of plant species richness. They argued that spatial and temporal nesting increased cost-effectiveness of assessing cumulative effects of diffuse impacts and numerous point sources. These studies demonstrate that ecologists have gradually realized that rather than struggle with controlling or minimizing spatial and temporal variations, they should incorporate and account for variation as well as natural history and other prior knowledge, including long-term monitoring data (Peters et al. 2006, Hewitt et al. 2007, Miao et al. Chapter 4).

1.3 Major Developments of Alternative Analytical Approaches

The development of non-replicated experimental designs has paralleled the development of alternative statistical analyses in the 1970s and 1980s, with advances in one providing impetus to the other. Alternative experimental designs such as BA, BACI, or BACIPS require analyzing time–series data within one site or comparing unreplicated impact and control sites. Intervention Analysis (Box and Tiao 1975a) based on a BA design used a mixed autoregressive moving average model and maximum likelihood estimates for model parameters to detect an effect resulting from a disturbance. Furthermore, Randomized Intervention Analysis (RIA), based on Monte Carlo simulations, was applied to detect whether an impacted ecosystem changed relative to a control ecosystem, while considering serial correlation within the time-series data (Carpenter et al. 1989). These methods were employed because the data did not meet classical statistical assumptions of an ordinary *t*-test: normality, constant variance, and independence. BACI designs, *t*-tests, or ANOVA models, with or without modifications for variance allocation, were applied after designing a sample scheme that would avoid serial correlation among the data and ascertaining whether the assumption of independence was met (Smith 2002). A *t*-test was proposed by Stewart-Oaten and Bence (2001) for the BACIPS design, while an asymmetric ANOVA was recommended by Underwood (1993, 1994) for the Beyond BACI design. However, an ecologist's statistical tools must move beyond the ANOVA paradigm (Grace et al. Chapters 2 and 11) to maximize our understanding of ecological systems and processes and identify the mechanisms that underlie ecosystem change, rather than simply accepting or rejecting a null hypothesis.

Contemporary statistical tools such as maximum likelihood, meta-analysis, information theory, Bayesian statistics, structural equation modeling (SEM), and inverse analysis, readily applied in other scientific fields including conservation biology, wildlife management, meteorology, and paleoecology are increasingly applied to ecology (Clark et al. 2001a, Holl et al. 2003, Pugesek et al. 2003, Grace et al. 2005, Green et al. 2005, Hilty et al. 2006, Hobbs and Hilborn 2006). Likelihood methods are extremely flexible when identifying best fit parameters, including strongly skewed and non-normal data (Aguiar and Sala 1999, Pawitan 2001, Hobbs and Hilborn 2006), allowing both linear and nonlinear models to fit to data. The likelihood approach also provides a basis for meta-analysis, information theory, and Bayesian analyses. Meta-analysis incorporates disparate, albeit carefully selected experimental data including pseudoreplicated studies, into a statistical statement of cumulative knowledge (Hedges and Olkin 1985, Hunt and Cornelissen 1997, Gurevitch et al. 2001). Bayesian statistics have received more attention than the others as a result of persistent efforts by a group of leading ecologists including Reckhow (1990), Ellison (1996, 2004), Lamon and Stow (2004), Clark (2005), and McCarthy (2007). Bayesian statistical models are designed to incorporate information from multiple sources to explicitly use results of previous studies as well as current experiments, observations, or manipulations. This multi-source feature allows relatively wide application for resource management and policy decisions. Bayesian models offer distinct advantages over classical null hypothesis testing. They provide a posterior probability distribution for the model parameters which potentially can be used to support a wide range of decisions that apply multiple decision criteria and prediction function testing, while approaches used in classical null hypothesis testing are much more constrained.

Structure Equation Model (SEM) is essentially a multivariate extension of regression and correlation analyses derived from the original concept of path analysis (Grace et al. Chapter 2). It is a powerful tool for inferring cause and effect relationships in the absence of experimental manipulation (Pugesek et al. 2003, Grace 2006) and therefore offers a more comprehensive, efficient, and effective framework than the traditional ANOVA-based experimental approaches for learning about processes from data (Grace et al. Chapter 2). Inverse analysis is an approach that focuses on data analysis to estimate parameters and their variability in order to evaluate model structure and information content of data. Overall, novel experimental design and analytical approaches such as those mentioned above are capable of addressing the complexity and uncertainty of large-scale ecosystem studies.

1.4 Ongoing Issues

These developments in design and analysis are not yet mainstream in ecological studies. In 1990, Carpenter and others contributed to a special edition of the journal *Ecology* in which they called for developing non-replicated experimental design and novel statistical analyses. In the 10 years (1990–2000) following Carpenter's appeal for development of new statistical methods, relatively few papers used BACI, BACIPS, MBACI, and similar approaches, with that number increasing slightly from 2000 to 2006. Since 1990, over 140 papers appeared in refereed journals that used a version of these methods: 42% in the USA, 19% in Australia–New Zealand, and 18% in Europe. Studies using BACI or one of its variants were conducted most frequently in aquatic ecosystems (marine 34%, freshwater 29%) while only 12% were conducted in forests. Fifty-three percent included animals (19% fisheries and 14% birds). Use of these analytical techniques was most common for impact assessment (53%) and management issues (11%), though more typical research questions (14%) were also reported. Surprisingly, only 13% of the articles addressed restoration and habitat improvement. Because this survey was conducted for scientific papers searchable online, this review is likely incomplete, and there may be a bias against some of the earlier research.

Numerous reasons exist for the lag in acceptance of alternative design and analytical approaches. First of all, ecologists traditionally have been trained to design field experiments using randomized complete block design or orthogonal designs with systematic or random sampling, particularly when prior knowledge about spatial structure and patterning of the system does not exist. Additionally, ecologists have long relied on a relatively narrow set of statistical techniques to ask questions that can be answered using existing statistical frameworks (Grace et al. Chapter 2). Hobbs and Hilborn (2006) pointed out that “There is danger that questions are chosen for investigation by ecologists to fit widely sanctioned statistical methods rather than statistical methods being chosen to meet the needs of ecological questions.” It is clear that students need experience conducting both traditional and novel analyses, but their professors, well versed in traditional analytical methods, are often not sufficiently experienced to engage their students in the use of novel approaches. Finally, established journals and their editors may shy away from reporting non-replicated designs and their associated data analyses because they, too, must obtain reviews from scientists who are most comfortable with classical approaches.

As part of our efforts to design a large-scale ecosystem study in the Florida Everglades, we (Miao and Carstenn 2005) attempted to integrate ecological research and management needs four years ago to advance the field of ecosystem ecology. In the process, we were confronted by many, if not most, of the design and analytical challenges addressed in this book. Echoing the concerns of the 1990 Ecology Special Feature, we organized a symposium for the 2006 Ecological Society of America (ESA) Annual Conference to share our and others’ experiences with integrating new statistical approaches into the design and analysis of large-scale and long-term ecosystem and landscape studies. Following the ESA Symposium and a *Frontiers in Ecology and the Environment* editorial (Miao and Carstenn 2006), we heard repeatedly from eminent and junior scientists alike that there is not only a need to change techniques but also a need for guidance and examples of “how to change.” In this book, we have united a group of scientists who have been working in the field of ecology for decades to present the ecological issues, challenges, novel solutions, and implications of their research.

1.5 Major Features of the Book

This book fills a unique niche in ecological methodology. It is neither a statistical book nor an experimental design book. Instead, it is a "how-to" book integrating design, analysis, and interpretation of large-scale and long-term case studies based on real-world ecological issues. Authors have emphasized their thought processes, communicating why they applied particular experimental designs and/or analytical approaches to answer their research questions. In doing so, each case study begins with issue identification; includes experimental design, analysis, and interpretation; and concludes with appropriate management recommendations. Each chapter emphasizes the reasoning behind the approach rather than simply the results of an experiment, giving each chapter a flavor very different from scientific journals. It offers a unique and rich “behind the scenes” learning experience to readers that they usually do not gain from scientific journal articles covering the same topics. This educational aspect encourages multiple readings of chapters where the approach may not be familiar.

Overall, the structure of the book is broken into design, analysis, and modeling. The book offers an array of alternative perspectives and options for the design and analysis of large-scale and long-term ecological studies (Table 1.1). Grace et al. (Chapter 2) critique conventional experimental practices that use ANOVA-based experimental approaches and strongly recommend rethinking the dominant role of ANOVA in ecological studies. ANOVA models (including their derivatives ANCOVA and MANOVA) have dominated ecological analyses and are often considered to be the preferred model for analyses. Overemphasized in the biological sciences, they are poorly suited to the analysis of systems. For example, one striking characteristic of the ANOVA approach is its use of "replications." In this book, authors from diverse backgrounds and ecological fields have shown that for many large-scale and long-term studies including watersheds, wetlands, fire, global climate change, landscape regime shifts, and paleoecology (Table 1.1), replication of ecosystem and landscape disturbances or treatments is neither possible nor desirable under real-world circumstances (Schindler 1998). Alternatives better suited to the study of multi-process system models deserve more attention (Grace et al. Chapter 2). It is time for large-scale ecological studies to develop alternatives rather than just applying replication and randomization to cope with system variation (Carpenter 1990, Hewitt et al. 2001, Hewitt et al. 2007, Miao et al. Chapter 4). For example, Canham and Pace (Chapter 8) employed an inverse approach to asking research questions about processes and answered their questions using an alternative modeling approach. They argue that instead of focusing on "statistical significance" of an effect of a manipulative experiment, ecosystem ecologists and/or resource managers should address the questions of where, when, and most importantly, how much a system was affected by the manipulation. Traditionally, ecologists and hydrologists have devoted enormous efforts to the intensive *direct* measurement of one or a few variables, yet these data provide little insight into predicting whole system performance. An inverse approach which asks "what would the rate of the process have to be given the data available" uses readily measured variables (e.g., lake chemistry) to model processes, then predicts process responses to changing variables.

Another unique feature of this book is that it not only stimulates scientific aspirations for alternative novel approaches but also provides diverse *solutions* to individual problems in research design, statistical analysis, and modeling approaches to assess ecological responses to natural and anthropogenic disturbances at ecosystem and landscape levels. Several chapters present readers with a clear picture of steps taken by the authors to move beyond the dilemmas they faced and overcame obstacles by linking design and analytical techniques. For example, Peters et al. (Chapter 3) outlined a multi-scale experimental design with relevant analytical techniques to examine the key processes influencing woody plant encroachment from fine to broad scales. Miao et al. (Chapter 4) applied multi-scale spatial controls to contend with variation arising from system spatial structure and asymmetric temporal sampling schemes for response variables which operate at different biological organization levels, thereby revealing both short- and long-term fire effects on a wetland ecosystem.

In addition to design, several chapters provide solid arguments and examples of alternative statistical methods to solve real-world problems, particularly those related to spatial and temporal variation. For example, Grace and colleagues (Chapter 2) applied SEM to two field experimental studies, plant diversity in coastal wetlands and the effects of thinning and burning on delayed mortality in Ponderosa pine forests. They illustrated how the application of SEM to ecological problems, especially large-scale studies, can contribute to the scientific understanding of natural systems. Stow and his colleagues (Chapter 5) advocate a popular cross-system approach for large-scale ecological inference in limnological studies (Cole et al. 1991). They developed several alternative multilevel Bayesian models for chlorophyll *a* concentrations and total phosphorus concentrations, and suggested that working in a Bayesian framework provides measures of uncertainty that can be used to evaluate the probability that management objectives will be achieved under differing strategies. Fortin and Melles (Chapter 6) analyzed spatial responses of avian bird species to forest spatial heterogeneity at the landscape level. They addressed data acquisition, resolution, spatial structure, and statistical analyses; identified statistical challenges that emerged while analyzing spatially autocorrelated data; and proposed a series of widely applicable analytical steps to help determine which spatial and numerical methods best estimated species' responses to changes in forest cover at the regional scale. McGowan and Leavitt (Chapter 7) highlighted the role of paleoecology in ecosystem science by demonstrating how the modes and causes of ecological variation can be identified by analysis of long time series (100–1000s year) using numerous statistical approaches, including ecosystem synchrony, variance partitioning analysis, and explicit spatial contrasts among lakes. These retrospective studies were used to generate clear management options for pressing environmental issues such as sustainable fisheries, management, and climate change.

Modeling efforts have been widely recognized and accepted for scaling-up traditional experiments and solving management problems. However, most current modeling approaches are still constrained when ecological and management issues are addressed on regional spatial scales and/or long temporal scales (King 1991, Tian et al. 1998, Tian et al. Chapter 9). Canham and Pace (Chapter 8) present a new approach to analyzing the linkages between watersheds and lakes based on a simple, spatially explicit, watershed-scale model of lake chemistry. Their modeling approach provides a means to test questions on regional scales using the power of data from large numbers of watersheds that produce robust parameter estimates and comparisons of models. Tian and others (Chapter 9) attempted to predict the growth of plants, animals, and ecosystems in the future when climate, CO_2, and other factors will likely differ greatly from today. They employed an integrated regional modeling approach to effectively reorganize data collected on multiple scales to make them consistent with the study scale while preventing information loss and distortion.

Luo and Hui (Chapter 10) applied inverse analysis to Duke Forest Free Air CO_2 Enrichment (FACE) experimental data demonstrating that uncertainty in both parameter estimations and carbon sequestration in forest ecosystems can be quantified. They argued that inverse analysis will play a more important role in global change ecology. The combination of forward and inverse approaches allows us to probe mechanisms underlying ecosystem responses to global change. Finally, Grace et al. (Chapter 11) presents a framework to describe how different types of analyses depend on the amount of data available and the amount of knowledge about mechanisms. The flexibility of model analysis procedures proposed permits a greater integration of process with data than up to this point, suggesting at least one way forward for the study of large-scale systems.

A further innovation of this book is that the authors present a comprehensive framework for ecological problem solving using new and recently published data (e.g., Chapters 4 and 6) rather than summaries of previously published research. Each chapter addresses the development of one or more new methodologies and their underlying philosophies to an extent that cannot usually be addressed adequately in a typical journal article. For each chapter, the methods are the primary message while the case study is the context in which the authors present their methods. This approach is intended to help researchers design and analyze their own work using similar methods by clearly connecting the challenges of ecological research, the limitations of traditional statistical paradigms, and the goals and purposes of scientific investigations.

Moreover, all chapters of the book were subjected to rigorous anonymous peer review. The chapters were first reviewed by the three editors, revised, and then submitted to two or three external reviewers to assure an extensive peer-review process. These reviews ensure more extensive critiques and editing than many journal articles receive.

Overall, from our unique perspectives, the authors of this book illustrate how we, as ecologists, can effectively address ecological questions under spatial, temporal, and budgetary constraints while using defensible quantitative but non-traditional techniques. The authors highlight successful case studies that use novel approaches to address large-scale or long-term environmental investigations. This collection of case studies showcases innovative experimental designs, analytical options, and interpretations currently available to theoretical and applied ecologists, practitioners, and biostatisticians. These case studies begin to address the challenges that ecologists increasingly face in understanding and explaining large-scale, long-term environmental change.

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