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Design and Analysis of Long-term Ecological Monitoring Studies

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Design and Analysis of Long-term Ecological Monitoring Studies

To provide useful and meaningful information, long-term ecological programs need to implement solid and efficient statistical approaches for collecting and analyzing data. This volume provides rigorous guidance on quantitative issues in monitoring, with contributions from world experts in the field. These experts have extensive experience in teaching fundamental and advanced ideas and methods to natural resource managers, scientists, and students.

The chapters present a range of tools and approaches, including detailed coverage of variance component estimation and quantitative selection among alternative designs; spatially balanced sampling; sampling strategies integrating design- and model-based approaches; and advanced analytical approaches such as hierarchical and structural equation modeling. Making these tools more accessible to ecologists and other monitoring practitioners across numerous disciplines, this is a valuable resource for any professional whose work deals with ecological monitoring.

Supplementary example software code is available online at www.cambridge.org/9780521191548.

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Foreword: Ecology, management, and monitoring

Ecological monitoring has a somewhat checkered history, in part because it has been a fuzzy concept. It has ranged from measuring a single variable at a single location over time to measuring multiple variables at a national scale, sometimes with quantitatively defensible designs and sometimes not. Most currently accepted definitions include measuring in some *convincing* way (and that adjective is critical) some aspect of ecological composition, structure, or function over time. In the past, managers have received more rewards from doing things than understanding the effectiveness of what they did. Funding for ecological monitoring, therefore, has been variable and usually has been the first victim of budget cuts. The scientific community has also been partly to blame. Where monitoring was employed, sometimes the wrong thing was measured, or measured in the wrong way. Monitoring was often designed with little attention to a conceptual framework, and seldom had a firm tie to policy and decision making.

In part due to this history, research and monitoring have been viewed as two distinct and separable activities. The former was seen as controlled, largely experimental, and rigorous, while the latter was seen as uncontrolled, largely observational, and inexact. This distinction has thankfully faded over time, and now research and monitoring are seen more as a continuum (Busch and Trexler 2003). Research is generally stronger at determining cause and effect. Monitoring contributes a spatial and temporal depth that is less commonly seen in research, and both are capable of testing hypotheses.

Ecological monitoring is as complex as the ecosystems it is intended to measure. Those ecosystems are in a constant state of flux. The only constant is change, and that change can be linear or nonlinear. Natural variation can make analysis difficult. Some populations will be naturally cyclic on an annual scale (salmon), or in the case of migratory animal populations, seasonally variable. Monitoring needs to acknowledge the following features of ecological systems: the significance of natural processes, the dynamic nature of ecological systems, the uncertainty and inherent variability of those systems, and the importance of cumulative effects (Dale *et al.* 1999).

How the system works, identified by conceptual models, is an important precursor to development of a monitoring plan. Evaluating ecosystem linkages helps to define the right things to measure, and may help in explaining the source of the ecological change being measured. Models help to justify and explain why a particular resource or species is important to measure.

Well-defined monitoring plans can help define ecological change in a reliable way. However, change alone is an insufficient metric for a monitoring plan. There must be thresholds of change that trigger action by managers, and managers need to be involved in defining those thresholds. This implicitly incorporates values in addressing ecological change as good, bad, or ugly. Consider a resource being monitored where, over time, dissimilarity among sites increases, remains stable, or decreases. Those data, independent of incorporating values, are not very meaningful without a management context. Increasing dissimilarity among sites may indicate increasing species richness, perhaps not desirable if invasive species are the cause. Decreasing dissimilarity among sites may indicate homogenization, perhaps desirable if disturbed sites are recovering to the levels of pristine sites, or perhaps undesirable if generalists are gaining at the expense of less common species. Management objectives provide an interpretive context for change. At some point, sufficient change occurs that management actions are needed, triggered not only by statistically significant change, but also its relevance to management objectives.

Ecological monitoring is an essential part of the process known as adaptive management (Holling 1978). Effective monitoring may show a need for new ecosystem assessments, new decisions concerning resource allocation or priorities for action, or changes in implementing actions. Substituting space for time (spatially separated sites where treatment occurred in the past) can provide short-term insights into the temporal change that might be expected over time, but is criticized due to assumptions of site uniformity before treatment/disturbance, uniformity of conditions following treatment/disturbance, and often subjective sampling designs. Ecological monitoring demands a patient approach, as most change in "noisy" ecosystems requires multiple years of data to provide reliable inference. Some monitoring protocols may be able to show change over a short time, but others may require a decade or two to show, for example, a 25% population change with 80% power at $\alpha = 0.10$. Higher sampling intensities may shorten that time, but with associated higher costs.

As scale increases from point to landscape, the issue of spatial balance of sampling emerges. Many monitoring plans are now at these larger ecoregion scales, so it is important to address sampling design as much as measurement methodology. Newer spatially balanced probability designs, such as the Generalized Random Tessellation Stratified Design (GRTS; Stevens and Olsen 2004) help in allowing unbiased inference from monitoring at these larger scales.

Monitoring programs still face many challenges. First, some monitoring plans are considered complete when they are not. In a recent survey of plant and animal population monitoring programs, only half the programs had determined in advance what statistical methods would be employed in evaluating change, and only 20% of the programs included issues of statistical power, with little difference between older (> 20 years) and recent (< 6 years) programs (Marsh and Trenham 2008). These data suggest that a majority of current monitoring plans (at least for plants and animals) are likely inept, due either to ignorance of statistics or a lack of ability to incorporate quantitative techniques. Those with excellent design and analysis will be of the highest utility to managers because statements of change (or lack of change) will be convincing. Second, stable funding of long-term monitoring is a real concern. Most funding institutions are public, and with that comes the inevitable cycle of periodic budget cuts associated with new laws, recessions, and the like. Ecological monitoring programs are in direct competition with social programs, and few have developed adequate rationales to compete with those programs in times of shrinking budgets. Not only is the scale of monitoring restricted when the budgets are cut, but the sample design itself may be compromised if only a portion of the monitoring can be funded.

These problems can be at least partly alleviated with defensible monitoring approaches. Rigorous design, implementation, and analysis for ecological monitoring are the wave of the future, destined to have the power of a tsunami. And the earthquake that spawns that tsunami is contained within the chapters of this book.

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Preface

Environmental monitoring is of fundamental importance to natural resource managers, scientists, and human society in general – consider the inarguable importance of quantifying changes in climate, air and water quality, surface and ground water dynamics, and similar attributes. However, monitoring studies also have the potential to be a significant waste of time and money (see, for example, discussions by Legg and Nagy 2006). To have value, a monitoring program needs to produce information of sufficient accuracy relevant to a clearly defined purpose, and to do so cost-effectively. Yet, even in the short term, natural populations and systems are inherently variable and usually difficult to study. Adding in a multi-year (usually multi-decade) focus creates many additional challenges and scales of uncertainty – and increases the potential amount of time and money wasted if these challenges are not adequately addressed. Many monitoring efforts have failed or will fail due to poorly defined objectives and inadequate designs (Yoccoz *et al.* 2001, Noon 2003, Legg and Nagy 2006, Lindenmayer and Likens 2010a). Yet, statisticians and ecologists have developed, and continue to develop, a rich body of knowledge and practical methods for addressing these challenges, and have applied these methods successfully at a variety of scales for a diversity of attributes. *Our goal for this volume is to help make some key components of this knowledge base, as well as new extensions, readily available and accessible to quantitative and applied natural resource scientists and managers, program managers, students, and consulting biometricians involved with environmental monitoring worldwide.*

We have simple motivations for producing this volume. As a result of three of the four editors' experience working or collaborating with the US National Park Service (NPS) Inventory and Monitoring Program, it became apparent that sampling tools and expert guidance not available in published texts were being regularly applied in the development of monitoring programs by or in partnership with the US Environmental Protection Agency (USEPA), US Geological Survey (USGS), NPS, and other entities. More generally, throughout the monitoring world, there were many pools of expertise and situations where existing analytical tools were being applied and extended for use in monitoring. However, much of this relevant expertise was not easily accessible to the broad audience of ecologists involved with monitoring. Information on a diversity of approaches, tools, and current developments was scattered widely in sources such as statistical journals, other texts not focused on monitoring, unpublished sources, and agency web pages, as well as in the collective professional experience of many biometricians and quantitative ecologists. We wanted to make this information and expertise more readily available to help all environmental monitoring programs increase their effectiveness and to stimulate further extensions of existing methods. Through this edited volume, we also wanted to help provide readers with diverse views and expert guidance directly from many world experts who have developed and guided the implementation of quantitative methodology in ecological monitoring.

Scope

This volume is intended to offer broad guidance on defining objectives for monitoring and on developing a survey design and analytical approach to meet these objectives. It is organized into five sections. The first section gives perspectives about defining the purpose for a monitoring program, an overview of important quantitative issues, and a review of the necessary statistical background for readers with relatively basic statistical training and knowledge. The second section focuses on critical issues and tools for designing monitoring programs – including probability sampling designs; planning the temporal component of monitoring; and estimating sources of variability that will affect the quality of information produced by the study. The third section focuses on a wide variety of methods and perspectives for analyzing monitoring data. Chapters in the fourth section focus on additional topics related to developing a monitoring program, planning a survey design, and analyzing data; this section focuses on advanced and specialized issues (e.g. hierarchical modeling, planning demographic monitoring of populations) and applications. The fifth, concluding, section illustrates how quantitative issues and other aspects of a monitoring program can be integrated, and how decisions about monitoring can be evaluated in the context of broader conservation and management goals of an organization.

This volume is intended to highlight general challenges in monitoring design and analysis, to demonstrate principles and some widely useful methods for addressing these challenges, and to provide perspectives from a diverse group of experts. Our goal is not to provide an exhaustive source of statistical methods or decision keys leading readers through the realm of design options to the specific approach they should use in their situation. Our expectation is that readers will use this volume in conjunction with general sampling texts, literature on monitoring, and other specialized references – and particularly in collaboration with statisticians with experience in monitoring. Similarly, chapter authors provide equations and software commands to help readers understand general methods, and steer readers to more specialized references for more detailed guidance.

Our intent was that every chapter in this volume would be relevant across a wide range of environmental disciplines. In terms of specific examples and scenarios discussed, there is a moderate bias towards wildlife-focused monitoring given the backgrounds of the editors, but the quantitative issues and tools discussed are of general importance. Conversely, some tools and approaches that have been a regular component of some large-scale monitoring programs, particularly programs coordinated by the USEPA, for >10 years (e.g. spatially balanced sampling) have become a standard part of the survey-design toolbox for other programs and disciplines only in the last few years. Therefore, while examples presented in chapters obviously are discipline-specific, chapters focus on concepts and methods of general importance to any environmental discipline. More generally, the volume offers a diversity of perspectives about how the experts involved see the world of environmental monitoring, and even how they define "monitoring".

Features

Technical accessibility

Besides relevance across disciplines, we also wanted this volume to have broad relevance to readers with varying levels of technical expertise and quantitative interests. We sought this breadth both at the level of the entire volume and within individual chapters. Collectively, chapters in the first and last sections ("Overview" and "Conclusion") focus less on quantitative details and more on large picture issues relevant to all readers. The middle sections focus on design and analysis, with most chapters focusing partly on technical details and considerations. All readers with some coursework or basic knowledge of applied environmental statistics should benefit from the general discussion in these chapters. In some chapters, ecologists with advanced backgrounds in statistics and some biometricians will benefit most from the technical details. In these latter cases, the authors remain focused on applied and practical issues, and on explaining methods at a level more accessible to ecologists compared to discussions in statistical journals. Most chapters include either multiple small real-world or realistic examples, or an extended case study, to make clear the relevance of the topics being discussed and to help readers better understand the application of methods discussed.

Chapter features

In addition, each chapter was structured to ensure its practical value to all readers, through the following features:

Introduction and summary. Each chapter has a general introduction and summary to document the context for the specific topics discussed in the chapter and to reiterate key messages.

Take-home messages. In the long term, time and money spent on sound statistical planning and investing in partnership with statistical experts pays off. However, time and money first need to be spent. Such investments require decisions by program managers and administrators who certainly want and need to understand the big picture, but possibly not all the technical details. Therefore, each chapter in this volume includes a "Take-home Messages for Program Managers" call-out box, to give readers the "big picture" in a less technical fashion and to help program managers see the relevance of the chapter to their program.

Common problems and difficult gray areas. The authors involved in this volume have extensive practical experience with monitoring programs, and understand possible common difficulties and sticking points related to their chapter. Therefore, chapters each have a "Common Challenges" call-out box in which authors briefly emphasize some common issues that readers likely will need to consider further as they apply what they learned.

Future research and development. To help define the limits of current knowledge or available tools and outline potential high-priority research/development needs, authors provide a *Future Research and Development* section near the end of each chapter. Moreover, the above-mentioned "Common Challenges" also often point out issues in need of further research and development of methodology.

Software applications

Software commands provided in chapters and online supplements are intended to point readers towards available tools (most commonly in R, SAS, or WinBUGS), help demonstrate the application of design and analytical approaches, and help some readers build on their existing knowledge to begin applying these approaches in their situations. In several cases, authors provide software code, background information, data sets used for example, and even analytical output as online supplements (www.cambridge.org/9780521191548). Authors usually steer readers to more extensive instruction and demonstration of software applications available from user's guides, web sites, specialized training, and other texts. (Throughout the volume, references to proprietary software by authors who are US government employees do not imply endorsement by the US government.)

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