

Preface

Why another book on statistics? The field is already crowded with texts on biometry, probability theory, experimental design, and analysis of variance. The short answer is that we have yet to find a single text that meets the two specific needs of ecologists and environmental scientists. The first need is a general introduction to probability theory including the assumptions of statistical inference and hypothesis testing. The second need is a detailed discussion of specific designs and analyses that are typically encountered in ecology.

This book reflects several collective decades of teaching statistics to undergraduate and graduate students at the University of Oklahoma, the University of Vermont, Mount Holyoke College, and the Harvard Forest. The book represents our personal perspective on what is important at the interface of ecology and statistics and the most effective way to teach it. It is the book we both wish we had in our hands when we started studying ecology in college.

A "primer" suggests a short text, with simple messages and safe recommendations for users. If only statistics were so simple! The subject is vast, and new methods and software tools for ecologists appear almost monthly. In spite of the book's length (which stunned even us), we still view it as a distillation of statistical knowledge that is important for ecologists. We have included both classic expositions as well as discussions of more recent methods and techniques. We hope there will be material that will appeal to both the neophyte and the experienced researcher. As in art and music, there is a strong element of style and personal preference in the choice and application of statistics. We have explained our own preferences for certain kinds of analyses and designs, but readers and users of statistics will ultimately have to choose their own set of statistical tools.

How To Use This Book

In contrast to many statistics books aimed at biologists or ecologists—"biometry" texts—this is not a book of "recipes," nor is it a set of exercises or problems

tied to a particular software package that is probably already out of date. Although the book contains equations and derivations, it is not a formal statistical text with detailed mathematical proofs. Instead, it is an exposition of basic and advanced topics in statistics that are important specifically for ecologists and environmental scientists. It is a book that is meant to be read and used, perhaps as a supplement to a more traditional text, or as a stand-alone text for students who have had at least a minimal introduction to statistics. We hope this book will also find a place on the shelf (or floor) of environmental professionals who need to use and interpret statistics daily but who may not have had formal training in statistics or have ready access to helpful statisticians.

Throughout the book we make extensive use of footnotes. Footnotes give us a chance to greatly expand the material and to talk about more complex issues that would bog down the flow of the main text. Some footnotes are purely historical, others cover mathematical and statistical proofs or details, and others are brief essays on topics in the ecological literature. As undergraduates, we both were independently enamored of Hutchinson's classic *An Introduction to Population Biology* (Yale University Press 1977). Hutchinson's liberal use of footnotes and his frequent forays into history and philosophy served as our stylistic model.

We have tried to strike a balance between being concise and being thorough. Many topics recur in different chapters, although sometimes in slightly different contexts. Figure and table legends are somewhat expansive because they are meant to be readable without reference to the text. Because Chapter 12 requires matrix algebra, we provide a brief Appendix that covers the essentials of matrix notation and manipulation. Finally, we have included a comprehensive glossary of terms used in statistics and probability theory. This glossary may be useful not only for reading this book, but also for deciphering statistical methods presented in journal articles.

Mathematical Content

Although we have not shied away from equations when they are needed, there is considerably less math here than in many intermediate level texts. We also try to illustrate all methods with empirical analyses. In almost all cases, we have used data from our own studies so that we can illustrate the progression from raw data to statistical output.

Although the chapters are meant to stand alone, there is considerable cross-referencing. Chapters 9–12 cover the traditional topics of many biometry texts and contain the heaviest concentration of formulas and equations. Chapter 12, on multivariate methods, is the most advanced in the book. Although we have tried to explain multivariate methods in plain English (no easy task!), there is

no way to sugar-coat the heavy dose of matrix algebra and new vocabulary necessary for multivariate analysis.

Coverage and Topics

Statistics is an evolving field, and new methods are always being developed to answer ecological questions. This text, however, covers core material that we believe is foundational for any statistical analysis. The book is organized around design-based statistics—statistics that are to be used with designed observational and experimental studies. An alternative framework is model-based statistics, including model selection criteria, likelihood analysis, inverse modeling, and other such methods.

What characterizes the difference between these two approaches? In brief, design-based analyses primarily address the problem of $P(\text{data} \mid \text{model})$: assessing the probability of the data given a model that we have specified. An important element of design-based analysis is being explicit about the underlying model. In contrast, model-based statistics address the problem of $P(\text{model} \mid \text{data})$ —that is, assessing the probability of a model given the data that are present. Model-based methods are often most appropriate for large datasets that may not have been collected according to an explicit sampling strategy.

We also discuss Bayesian methods, which somewhat straddle the line between these two approaches. Bayesian methods address $P(\text{model} \mid \text{data})$, but can be used with data from designed experiments and observational studies.

The book is divided into three parts. Part I discusses the fundamentals of probability and statistical thinking. It introduces the logic and language of probability (Chapter 1), explains common statistical distributions used in ecology (Chapter 2), and introduces important measures of location and spread (Chapter 3). Chapter 4 is more of a philosophical discussion about hypothesis testing, with careful explanations of Type I and Type II errors and of the ubiquitous statement that “ $P < 0.05$.” Chapter 5 closes this section by introducing the three major paradigms of statistical analysis (frequentist, Monte Carlo, and Bayesian), illustrating their use through the analysis of a single dataset.

Part II discusses how to successfully design and execute observational studies and field experiments. These chapters contain advice and information that is to be used before any data are collected in the field. Chapter 6 addresses the practical problems of articulating the reason for the study, setting the sample size, and dealing with independence, replication, randomization, impact studies, and environmental heterogeneity. Chapter 7 is a bestiary of experimental designs. However, in contrast to almost all other texts, there are almost no equations in this chapter. We discuss the strengths and weaknesses of different designs without get-

ting bogged down in equations or analysis of variance (ANOVA) tables, which have mostly been quarantined in Part III. Chapter 8 addresses the problem of how to curate and manage the data once it is collected. Transformations are introduced in this chapter as a way to help screen for outliers and errors in data transcription. We also stress the importance of creating metadata—documentation that accompanies the raw data into long-term archival storage.

Part III discusses specific analyses and covers the material that is the main core of most statistics texts. These chapters carefully develop many basic models, but also try to introduce some more current statistical tools that ecologists and environmental scientists find useful. Chapter 9 develops the basic linear regression model and also introduces more advanced topics such as non-linear, quantile, and robust regression, and path analysis. Chapter 10 discusses ANOVA (analysis of variance) and ANCOVA (analysis of covariance) models, highlighting which ANOVA model is appropriate for particular sampling or experimental designs. This chapter also explains how to use *a priori* contrasts and emphasizes plotting ANOVA results in a meaningful way to understand main effects and interaction terms. Chapter 11 discusses categorical data analysis, with an emphasis on chi-square analysis of one- and two-way contingency tables and log-linear modeling of multi-way contingency tables. The chapter also introduces goodness-of-fit tests for discrete and continuous variables. Chapter 12 introduces a variety of multivariate methods for both ordination and classification. The chapter closes with an introduction to redundancy analysis, a multivariate analog of multiple regression.

About the Cover

The cover is an original still life by the ecologist Elizabeth Farnsworth, inspired by seventeenth-century Dutch still-life paintings. Netherlands painters, including De Heem, Claesz, and Kalf, displayed their skill by arranging and painting a wide range of natural and manmade objects, often with rich allusions and hidden symbolism. Elizabeth's beautiful and biologically accurate renderings of plants and animals follow a long tradition of biological illustrators such as Dürer and Escher. In Elizabeth's drawing, the centerpiece is a scrolled pen-and-paper illustration of Bayes' Theorem, an eighteenth-century mathematical exposition that lies at the core of probability theory. Although modern Bayesian methods are computationally intensive, an understanding of Bayes' Theorem still requires pen-and-paper contemplation.

Dutch still lifes often included musical instruments, perhaps symbolizing the Pythagorean beauty of music and numbers. Elizabeth's drawing incorporates Aaron's bouzouki, as the writing of this book was interwoven with many sessions of acoustic music with Aaron and Elizabeth.

The human skull is the traditional symbol of mortality in still life paintings. Elizabeth has substituted a small brain coral, in honor of Nick's early dissertation work on the ecology of subtropical gorgonians. In light of the current worldwide collapse of coral reefs, the brain coral seems an appropriate symbol of mortality. In the foreground, an *Atta* ant carries a scrap of text with a summation sign, reminding us of the collective power of individual ant workers whose summed activities benefit the entire colony. As in early medieval paintings, the ant is drawn disproportionately larger than the other objects, reflecting its dominance and importance in terrestrial ecosystems. In the background is a specimen of *Sarracenia minor*, a carnivorous plant from the southeastern U.S. that we grow in the greenhouse. Although *Sarracenia minor* is too rare for experimental manipulations in the field, our ongoing studies of the more common *Sarracenia purpurea* in the northeastern U.S. may help us to develop effective conservation strategies for all of the species in this genus.

The final element in this drawing is a traditional Italian Renaissance chicken carafe. In the summer of 2001, we were surveying pitcher plants in remote bogs of the Adirondack Mountains. At the end of a long field day, we found ourselves in a small Italian restaurant in southern Vermont. Somewhat intemperately, we ordered and consumed an entire liter-sized chicken carafe of Chianti. By the end of the evening, we had committed ourselves to writing this book, and "The Chicken"—as we have always called it—was officially hatched.

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