Chapter 1 Introduction

1.1 Almost every biological theory or hypothesis is a model of how nature works
1.2 We use data to separate wrong models from (possibly) correct ones (or bad models from less bad ones)
  1.2.1 What kind of data do we need?
  1.2.2 The Signal and the Noise
  1.2.3 Random & representative
  1.2.4 How do we decide if a model fits well? What's the "best" model?
  1.2.5 What do I do next?
1.3 There are many ways to reach wrong conclusions!
1.4 There are also many ways to be right
1.5 Our philosophy in this book
  1.5.1 Think clearly
  1.5.2 Think in advance
  1.5.3 Think before you analyze
1.6 How this book is structured
1.7 A bit of housekeeping

Chapter 2 Things to know before proceeding

2.1 Samples, populations and statistical inference
2.2 Probability
2.3 Probability distributions
  2.1.1 Distributions for variables
  2.1.2 Distributions for statistics
2.4 Frequentist ("classical") estimation
  2.1.3 Simple parameters and statistics
    2.4.1.1 Center (location) of distribution
    2.4.1.2 Spread or variability
  2.1.4 Sampling distribution of the mean
  2.1.5 Standard error of the sample mean
  2.1.6 Confidence intervals for population mean
    2.4.1.3 Interpretation of confidence intervals for population mean
  2.1.7 Standard errors and confidence intervals for other statistics
  2.1.8 Resampling methods for frequentist estimation
    2.4.1.4 Bootstrap
    2.4.1.5 Jackknife
2.5 Hypothesis testing
  2.1.9 Frequentist statistical hypothesis testing
  2.1.10 Decision errors
  2.1.11 One- and two-tailed tests
  2.1.12 Multiple hypothesis testing
    2.5.1.1 Adjusting threshold levels or P-values
    2.5.1.2 False discovery rates
  2.1.13 Testing hypotheses about means and variances for two populations
  2.1.14 Parametric tests and their assumptions
    2.5.1.3 Robust parametric tests
    2.5.1.4 Randomization (permutation) tests
    2.5.1.5 Rank-based non-parametric tests
2.6 Comments on frequentist inference
2.7 Bayesian statistical inference
  2.1.15 Prior knowledge and probability
  2.1.16 Likelihood function
  2.1.17 Posterior probability
  2.1.18 Model comparison and Bayes factors
  2.1.19 Final comments

Chapter 3 Sampling and Experimental Design

3.1 Sampling Design
3.1.1 Probability Sampling
Simple Random Sampling
Stratified Sampling
Cluster Sampling
Systematic Sampling
Unequal Probability Sampling
Adaptive Sampling
3.1.2 Sample Size for Random Sampling
3.1.3 Non-probability Sampling
3.1.3.1 Convenience Sampling
Haphazard Sampling
Purposive Sampling
3.2 Experimental Design
3.2.1 Replication of Experimental Units
3.2.2 Controls
3.2.3 Randomization
3.2.4 Independence
3.2.5 Reducing Unexplained Variance
3.2.6 Limitations of Manipulative Experiments
3.3 Sample Size for Detecting Differences - Power Analysis
3.3.1 Using Power to Plan Experiments (*a priori* Power Analysis)
3.3.1.1 Sample Size Calculation (Power, σ, α, ES Known)
3.3.1.2 Effect Size Calculation (Power, n, σ, Known)
3.3.1.3 Sequence for Using Power Analysis to Design Experiments
3.3.2 *Post hoc* Power Calculation
3.3.3 Effect Size
What if we can't Identify an Effect Size about which we feel Confident?
3.3.4 Using Power Analyses
3.4 Further Reading

Chapter 4 Introduction to Linear Models

4.1 What is a linear model?
4.2 Components of Linear Models
4.2.1 Types of Response Variables
4.2.1.1 Continuous Response Variables
4.2.1.2 Discrete Response Variables
4.2.2 Types of Predictor Variables
4.2.2.1 Categorical (Discrete) vs. Continuous
4.2.2.2 Fixed vs. Random
4.3 Assembling our Linear Model
4.4 Estimation for Linear Models
4.4.1 Ordinary Least Squares
4.4.2 Maximum Likelihood
4.4.3 Robust Estimation Methods for Linear Models
4.5 How Well Does a Model Fit?
4.5.1 OLS Measures of Fit: Analysis of Variance
4.5.2 ML Measures of Fit: Log-likelihood and Deviance
4.5.3 Information Criteria
4.6 Assumptions for Linear Model Inference
4.6.1 Assumptions for OLS
4.6.1.1 Zero Conditional Mean of Errors
4.6.1.2 Independence of Errors
4.6.1.3 Homogeneity of Error Variances
4.6.1.4 Normality of Errors
4.6.1.5 Solutions
4.6.2 Assumptions for ML
4.6.3 Model Diagnostics
4.7 Types of Linear Models

4.7.1 General Linear Models
4.7.1.1 Continuous Response and Predictor(s) – "Regression" Models
4.7.1.2 Continuous (Normal) Response and Categorical Predictors – "ANOVA" Models
4.7.2 Generalized Linear Models
4.7.2.1 Binary Response, Continuous Predictor(s): Logistic Models
4.7.2.2 Poisson Response, Continuous Predictor(s)
4.7.2.3 Contingency Tables: Loglinear Model
4.7.3 Linear Mixed Models (General and Generalized)
4.8 Further Reading

Chapter 5 Exploratory Data Analysis

5.1 Basic Graphical Tools
5.1.1 Some Common Basic Graphs
5.1.1.1 Histogram
5.1.1.2 Dotplot
5.1.1.3 Boxplot
5.1.1.4 Probability Plot
5.1.1.5 Scatterplot
5.1.1.6 Scatterplot Matrix (SPLOM)
5.1.2 Smoothing
5.1.3 Residual Plots
5.2 Outliers
5.3 Am I Fitting the Right Model?
5.3.1 The Underlying Probability Distribution
5.3.2 Homogeneity of Variances
5.3.3 Is my Linear Model "Linear"?
5.4 Is it Normal to Transform Data?
5.4.1 Transformations and Distributional Assumptions
5.4.2 Transformations and Linearity
5.4.3 Transformations and Additivity
5.4.4 Do we Really Need a Data Transformation?
5.5 Standardizations
5.6 Missing Data
5.6.1 Missing Data Mechanisms
5.6.2 Detecting Missing Data
5.6.3 Methods for Missing Data
5.6.3.1 Deletions
5.6.3.2 Single Imputation
5.6.3.3 Multiple Imputation
5.7 Further Reading

Chapter 6 Simple Linear Models with One Predictor

6.1 Linear Model for a Single Continuous Predictor - Linear Regression
6.1.1 Linear Model for a Continuous Predictor (Linear Regression Model)
6.1.2 Model Parameters
6.1.2.1 Regression Slope
6.1.1.1 Intercept
6.1.1.2 Predicted Values
6.1.1.3 Error Terms and Their Variance
6.1.1.4 Standardized Coefficients
6.1.3 Inference for Parameters
6.1.1.5 Standard Errors and Confidence Intervals
6.1.1.6 Statistical Hypotheses
6.1.2 Inference for Predicted Values
6.1.4 Model Comparison and the Analysis of Variance
6.1.3 Regression Through the Origin
6.1.4 Regression with *X* Random
6.2 Linear model for a Single Categorical Predictor (Factor)

6.2.1.1 Completely Randomized (Experimental) Designs
6.2.1.2 Observational (Non-experimental) Designs
6.2.2 Linear Model for a Categorical Predictor
6.2.2.1 Linear Effects Model
6.2.2.2 Means Model
6.2.2.3 Regression (Dummy Variable) Model
6.2.3 Model Parameters
6.2.3.1 Predicted Values
6.2.3.2 Error Terms and Their Variance
6.2.4 Inference for Parameters
6.2.4.1 Standard Errors and Confidence Intervals
6.2.4.2 Hypothesis Tests
6.2.5 Model Comparison and the Analysis of Variance
6.2.6 Unequal Sample Sizes (Unbalanced Designs)
6.2.7 Specific Comparisons of Group Means
6.2.7.1 Planned Comparisons or Contrasts
6.2.7.2 Unplanned Pairwise Comparisons
6.2 Predictor effects
6.2.1 Continuous Predictor (Regression) Models
6.2.2 Categorical Predictor Models
6.3 Assumptions
6.3.1 Zero Conditional Mean
6.3.2 Independence
6.3.3 Variance Homogeneity
6.3.4 Normality
6.4 Model Diagnostics
6.4.1 Residuals
6.4.2 Leverage
6.4.3 Influence Measures
6.4.4 Diagnostic Plots
***6.4.4.1** Scatterplots*
6.4.4.2 Boxplots
6.4.4.3 Residual Plots
6.4.5 Transformations
6.5 Robust Linear Models
6.5.1 Rank-based ("Nonparametric") Methods
6.5.1.1 Continuous Predictor (Regression)
6.5.1.2 Categorical Predictor
6.5.2 Generalized (Weighted) Least Squares
6.5.3 Other Robust Methods
6.5.3.1 Categorical Predictors - Handling Heterogeneous Variances
6.5.4 Resampling and Permutation Methods
6.6 Power of Single Predictor Linear Models
6.6.1 Regression Models
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Chapter 7 Linear Models for Factorial (Crossed) Designs

7.1 Two Factor Fully Factorial (Crossed) Designs
7.1.1 Completely Randomized (Experimental) Designs
7.1.2 Observational (Non-experimental) Designs
7.1.3 Designs that Combine Completely Randomized Factors with Non-randomized (Observational) Factors
7.1.4 The Factorial Linear Effects Model
7.1.5 Model Parameters
7.1.5.1 Predicted values
7.1.5.2 Error terms and their variance
7.1.6 Inference for Parameters
7.1.6.1 Standard errors and confidence intervals
7.1.7 Model Comparison and Analysis of Variance

7.1.7.1 Balanced Designs
7.1.7.2 Unbalanced Designs
7.1.8 More on Main Effects and Interactions
7.1.9 Interactions and Transformations
7.1.10 Specific Comparisons of Marginal Means
7.1.11 Interpreting Interactions
7.1.11.1 Graphs
7.1.11.2 Simple Main Effects
7.1.11.3 Treatment–Contrast and Contrast–Contrast Interactions
7.1.12 Predictor Effects
7.1.13 Assumptions
7.1.14 Robust Factorial ANOVAs
7.2 Complex Factorial Designs
7.2.1 Missing Cells
7.2.2 Fractional Factorial Designs
7.3 Power and Sample Size in Factorial Designs

Chapter 8 Multiple Regression Models

8.1 Linear Model for Multiple Continuous Predictors – Multiple Regression
8.1.1.1 Cricket Jump Distance
8.1.1.2 Bird Abundance in Forest Patches
8.1.2 Linear Model for Two or More Continuous Predictors (Multiple Linear Regression Model)
8.1.3 Model Parameters
8.1.3.1 Intercept and Partial Regression Slopes
8.1.3.2 Predicted Values
8.1.3.3 Error Terms and Their Variance
8.1.3.4 Standardized Partial Regression Slopes
8.1.4 Inference for Parameters
8.1.4.1 Standard Errors and Confidence Intervals
Statistical Hypotheses
8.1.5 Model Comparison and Analysis of Variance
8.1.6 Assumptions of Multiple Linear Regression Models
8.1.7 Model Diagnostics
8.1.7.1 Leverage
8.1.7.2 Residuals
8.1.7.3 Influence
8.1.8 Diagnostic Graphics
8.1.8.1 Scatterplots
8.1.8.2 Residual Plots
8.1.9 Transformations
8.1.10 Collinearity
8.1.10.1 Detecting Collinearity
8.1.10.2 Dealing with Collinearity
8.1.11 Interactions in Multiple Regression
8.1.12 Regression Models with Polynomial Terms
8.1.13 Other Issues in Multiple Linear Regression
8.1.13.1 Regression Through the Origin
8.1.13.2 Weighted (generalized) least squares
8.1.13.3 X random (Model II regression)
8.1.13.4 Robust Regression
8.1.13.5 Missing Data
8.1.13.6 Power of Tests
8.1.14 Categorical Predictors in Multiple Regression Models
8.2 Analysis of Covariance
8.2.1 Linear Models for Simple Analyses of Covariance
Predicted Values and Residuals
8.2.2 Model Comparison and the Analysis of (Co)variance
8.2.3 Assumptions of ANCOVA Models
8.2.4 Homogeneous Within-group Regression Slopes

8.2.4.1 Evaluating Within-group Regression Slopes
8.2.4.2 Dealing with Heterogeneous Within-group Regression Slopes
8.2.5 Robust ANCOVA
8.2.6 Unequal Sample Sizes (Unbalanced Designs)
8.2.7 Specific Comparisons of Adjusted Means
8.2.7.1 Planned comparisons
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8.2.8 Factorial Designs
8.2.9 Designs with Two or More Covariates

Chapter 9 Predictor Importance and Model Selection in Multiple Regression Models

9.1 Relative Predictor Importance
9.1.1 Single Model Methods
9.1.1.1 Standardized Partial Regression Slopes
9.1.1.2 Tests on Partial Regression Slopes
9.1.2 Multiple Model Methods
9.1.2.1 Change in Explained Variation
9.1.2.2 LMG and Hierarchical Partitioning
9.1.2.3 Proportional Marginal Variance Decomposition (PVMD)
9.1.3 Recommendations of Relative Importance
9.2 Model Selection
9.2.1 Model Selection Criteria
9.2.1.1 Comparisons to Full Model
9.2.1.2 Information Criteria
9.2.2 Traditional Stepwise Selection
9.2.3 All Subsets and Information Criteria
9.2.4 Model Averaging
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9.3 Regression Trees
9.3.1 Standard Regression Trees
9.3.2 Bagging and Boosted Regression Trees

Chapter 10 Random Factors in Factorial and Nested Designs

10.1 Fixed vs. Random Effects and Mixed Models
10.1.1 Designs Applicable to Mixed Models
10.1.1.1 Single Random Factor Designs
10.1.1.2 Nested or Hierarchical Designs
10.1.1.3 Crossed and Block Designs
10.1.1.4 Split-plot Designs
10.1.1.5 Repeated Measures (RM) and Longitudinal Designs
10.2 Fitting Linear Models with Fixed and Random Factors
10.2.1 Traditional OLS "ANOVA" Models Approach
10.2.1.1 Estimation and Tests
10.2.1.2 Assumptions and Diagnostics
10.2.1.3 Overview
10.2.2 Linear Mixed Effect (or Multilevel) Models Approach
10.2.2.1 Estimation
10.2.2.2 Assumptions and Diagnostics
10.2.2.3 Overview
10.2.3 Modeling Strategies
10.3 Simple Random Factor Designs
10.3.1 Traditional OLS Approach
10.3.2 Linear Mixed effects (Multilevel) Models
10.4 Multilevel Regressions
10.5 Nested (Hierarchical) Designs
10.5.1 Two-level Nested Designs
10.5.1.1 OLS Analysis
10.5.1.2 Mixed Effects Model Analysis

10.5.1.3 Pooling and Model Selection in Nested Analyses
10.5.2 More Complex Nested Designs
10.5.3 Sample Size and Nested Designs
10.6 Factorial Mixed Designs
10.6.1 Types of Factorial Mixed Designs
10.6.1.1 General Factorial Mixed Designs
10.6.1.2 Randomized Block Designs
10.6.2 Analysis of Crossed Designs with One Fixed and One Random Factor
10.6.2.1 OLS Analysis
10.6.2.2 Linear Mixed Effects (Multilevel) Model
10.6.3 Crossed Designs with Two or More Fixed Factors and One Random Factor
10.1.2 Design and Analysis Issues with Crossed Mixed Designs and Their Models
10.6.3.1 Number of Random Factor Groups
10.6.3.2 Issues with Multiple Random Factors
10.6.3.3 Efficiency of Blocking
10.6.3.4 Missing Values in CB Designs
10.6.3.5 Incomplete Block and Latin Square Designs

Chapter 11 Split-plot (Split-unit) Designs: Partly Nested Models

11.1 Three-Factor Split-Plot Designs
11.1.1 Analysis for Three-Factor Split-Plot Designs
11.1.1.1 Linear Models for Split-Plot Designs
11.1.1.2 ANOVA and Estimates of Effects
11.1.1.3 Null Hypotheses
11.1.1.4 Split-Plots with Subplot Replication
11.1.2 Assumptions
11.1.3 Unbalanced Split-Plot Designs
11.1.4 Model Building
11.2 More Complex Designs
11.2.1 Additional Between-Plots Factors
11.2.2 Additional Within-Plots Factors
11.2.3 Including Continuous Covariates

Chapter 12 Repeated measures designs

12.1 Simple Repeated Measures Designs
12.1.1 Analysis of Simple Repeated Measures Designs
12.1.1.1 Linear Models for Simple Repeated Measures Designs
12.1.2 Assumptions for Simple Repeated Measures Models
12.1.2.1 Independence and Covariance Structures
12.1.3 Missing Observations
12.2 More Complex Repeated Measures Designs
12.2.1 One Between-subjects Factor
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12.2.4 Model Selection in Complex Repeated Measures Designs

Chapter 13 Generalized Linear Models for Categorical Responses

13.1 Logistic Regression
13.1.1 Binary Response with a Single Continuous Predictor – Simple Logistic Regression
13.1.2 Categorical Predictors in GLMs
13.1.3 Binary Response with Multiple Predictors – Multiple Logistic Regression
13.1.4 Nominal and Ordinal Multinomial Response Variables
13.1.5 Proportion Response
13.2 Count Responses – Poisson Regression
13.3 Goodness-of-fit for GLMs
13.4 Inference for Parameters in GLMs
13.5 Assumptions and Diagnostics for Binomial and Poisson GLMs

13.6 Over-dispersed Data
13.6.1 Identifying Overdispersion
13.6.2 Correcting for Overdispersion
13.6.2.1 Quasi-likelihood (Quasi-Poisson) Models
13.6.2.2 Negative Binomial Models
13.6.2.3 Including Observation-level Random Effects
13.6.3 Too Many Zeros (Zero-inflated Data)
13.6.4 Zero-truncated Data
13.6.5 Binomial Overdispersion
13.7 Contingency Tables
13.7.1 Two-way Tables
13.7.1.1 Test for Independence
13.7.1.2 Odds and Odds Ratios
13.7.1.3 Residuals
13.7.1.4 Small Sample Sizes
13.7.1.5 Loglinear Models
13.7.2 Three-way and Higher Tables
13.7.2.1 Three-way Interaction
13.7.2.2 Conditional (In)dependence
13.7.2.3 Joint Independence
13.7.2.4 Marginal Independence
13.7.2.5 Complete Independence
13.7.2.6 Hierarchical Loglinear Modeling
13.7.3 More Complex Tables
13.7.4 Loglinear Versus Logistic Models for Tables
13.8 Generalized Linear Mixed Models (GLMMs)
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Chapter 14 Introduction to Multivariate Analyses

14.1 Multivariate Data
14.2 Distributions and Associations
14.3 Linear Combinations, Eigenvectors, and Eigenvalues
14.3.1 Linear Combinations of Variables
14.3.2 Eigenvalues
14.3.3 Eigenvectors
14.3.4 Derivation of Components
14.4 Multivariate Distance and Dissimilarity Measures
14.4.1 Dissimilarity Indices for Continuous and Count Variables
14.4.1.1 Metric Measures
14.4.1.2 Semimetric
14.4.2 Dissimilarity Indices for Dichotomous (Binary) Variables
14.4.3 General Dissimilarity Indices for Mixed Variables
14.4.4 Choosing Dissimilarity Indices
14.5 Data Transformation and Standardization
14.6 Standardization, Association, and Dissimilarity
14.7 Screening Multivariate Data Sets
14.8 Introduction to Multivariate Analyses

Chapter 15 Multivariate analyses based on eigenanalyses

15.1 Principal components analysis
15.1.1 Deriving components
15.1.1.1 Axis rotation
15.1.1.2 Decomposing an association matrix
15.1.2 Interpreting the components
15.1.3 How many components to retain?
15.1.3.1 Eigenvalue equals one rule
15.1.3.2 Scree diagram
15.1.3.3 Broken stick criterion

15.1.3.4 Tests of eigenvalue equality
15.1.3.5 Other methods
15.1.4 Which association matrix to use?
15.1.5 Simplifying component structure
15.1.6 PCA assumptions and "fit"
15.1.6.1 Assumptions
15.1.6.2 PCA fit: residuals
15.1.7 Ordination and biplots for PCA
15.1.8 Principal components regression (PCR)
15.1.9 Factor analysis
15.2 Correspondence analysis
15.2.1 Deriving the axes
15.2.2 Ordination and biplots for CA
15.2.3 Reciprocal averaging
15.3 Use of PCA and CA with ecological abundance (count) data
15.4 Constrained (canonical) multivariate analysis
15.4.1 Redundancy analysis (RDA)
15.4.2 Canonical correspondence analysis
15.5 Linear discriminant function analysis
15.5.1 Deriving discriminant functions
15.5.2 Classification and prediction
15.5.3 Assumptions of discriminant function analysis
15.5.4 Multivariate analysis of variance (MANOVA)

Chapter 16 Multivariate analyses based on (dis)similarities or distances

16.1 Multidimensional scaling or ordination
16.1.1 Classical (metric) scaling – principal coordinates analysis (PCoA)
16.1.2 Nonmetric (enhanced) multidimensional scaling
16.1.2.1 Deriving the ordination
16.1.2.2 Interpretation of ordination plot
16.2 Cluster analysis
16.2.1 Agglomerative hierarchical clustering
16.3 Divisive hierarchical clustering
16.3.1 Non-hierarchical clustering
16.4 Analyses based on dissimilarities
16.4.1 Contributions of original variables to ordination
16.4.2 Relating dissimilarities to other variables
16.4.2.1 Mantel test
16.4.2.2 Bio-env
16.4.2.3 Matrix regression
16.4.2.4 Analysis of similarities
16.4.2.5 Multi-response permutation procedures
16.4.2.6 Comparing dispersions
16.4.3 Multivariate linear models
16.4.3.1 Distance-based redundancy analysis
16.4.3.2 Permutational multivariate analysis of variance (PERMANOVA)
16.4.3.3 MV-ABUND

Chapter 17 Telling stories with data

17.1 Research doesn't exist until you tell someone
17.1.1 Telling better stories: the importance of narrative
17.2 Summarizing data analyses
17.2.1 Linear models
17.2.1.1 Continous predictors
17.2.1.2 Categorical predictors
17.2.2 Other analyses
17.3 Visualizing data
17.3.1 Just show us the numbers!

17.3.2 Tables
17.4 Graphical summaries of the data
17.4.1 Some basic principles for visualizing data
17.4.1.1 Focus attention where you want it
17.4.1.2 Eliminate clutter
17.4.1.3 White (blank) space is good
17.4.1.4 The nitty-gritty: scales, ticks, labels and legends
17.4.2 An appropriate visual display
17.4.2.1 Bar graph
17.4.2.2 Line graph
17.4.2.3 Scatterplots
17.4.2.4 Pie charts
17.4.2.5 Slope charts
17.4.2.6 The challenge of –omics and other big data
17.5 ~~Error bars~~: visualizing variation and precision
17.5.1 Possible solutions
17.6 Horses for courses: what you present depends on who's listening
17.6.1 Know your audience as well as possible
17.6.1.1 Talks
17.6.1.2 Conferences and seminars
17.6.1.3 Talks with handouts (lecture, briefing, etc.)
17.6.1.4 Written stories (papers, theses, etc.)
17.7 Software and other sources
17.8 A reminder about storytelling