



Contents

Preface xii

1. Complex ecological data sets

- 1.0 Numerical analysis of ecological data 1
- 1.1 Spatial structure, spatial dependence, spatial correlation 8
 - 1 – Origin of spatial structures, 11; 2 – Tests of significance in the presence of spatial correlation, 17; 3 – Classical sampling and spatial structure, 21*
- 1.2 Statistical testing by permutation 22
 - 1 – Classical tests of significance, 22; 2 – Permutation tests, 25; 3 – Numerical example, 28; 4 – Remarks on permutation tests, 29*
- 1.3 Computer programs and packages 32
- 1.4 Ecological descriptors 33
 - 1 – Mathematical types of descriptors, 34; 2 – Intensive, extensive, additive, and non-additive descriptors, 37*
- 1.5 Coding 39
 - 1 – Linear transformation, 40; 2 – Nonlinear transformations, 41; 3 – Combining descriptors, 43; 4 – Ranging and standardization, 43; 5 – Implicit transformation in association coefficients, 45; 6 – Normalization, 45; 7 – Dummy variable coding, 52*
- 1.6 Missing data 54
 - 1 – Delete rows or columns, 55; 2 – Accommodate algorithms to missing data, 55; 3 – Estimate missing values, 55*
- 1.7 Software 57

2. Matrix algebra: a summary

- 2.0 Matrix algebra 59
- 2.1 The ecological data matrix 60
- 2.2 Association matrices 63
- 2.3 Special matrices 64
- 2.4 Vectors and scaling 69

2.5	Matrix addition and multiplication	71
2.6	Determinant	76
2.7	Rank of a matrix	80
2.8	Matrix inversion	82
2.9	Eigenvalues and eigenvectors	89
	<i>1 – Computation, 90; 2 – Numerical examples, 92</i>	
2.10	Some properties of eigenvalues and eigenvectors	99
2.11	Singular value decomposition	103
2.12	Software	107
3.	Dimensional analysis in ecology	
3.0	Dimensional analysis	109
3.1	Dimensions	110
3.2	Fundamental principles and the Pi theorem	115
3.3	The complete set of dimensionless products	130
3.4	Scale factors and models	138
4.	Multidimensional quantitative data	
4.0	Multidimensional statistics	143
4.1	Multidimensional variables and dispersion matrix	144
4.2	Correlation matrix	151
4.3	Multinormal distribution	157
4.4	Principal axes	165
4.5	Multiple and partial correlations	171
	<i>1 – Multiple linear correlation, 173; 2 – Partial correlation, 175; 3 – Tests of statistical significance, 180; 4 – Causal modelling using correlations, 182</i>	
4.6	Tests of normality and multinormality	187
4.7	Software	194
5.	Multidimensional semiquantitative data	
5.0	Nonparametric statistics	195
5.1	Quantitative, semiquantitative, and qualitative multivariates	197
5.2	One-dimensional nonparametric statistics	201
5.3	Rank correlations	205
	<i>1 – Spearman r, 205; 2 – Kendall τ, 209</i>	

- 5.4 Coefficient of concordance 213
1 – Computing Kendall W, 214; 2 – Testing the significance of W, 216; 3 – Contributions of individual variables to Kendall's concordance, 217

- 5.5 Software 218

6. Multidimensional qualitative data

- 6.0 General principles 219
- 6.1 Information and entropy 220
- 6.2 Two-way contingency tables 228
- 6.3 Multiway contingency tables 235
- 6.4 Contingency tables: correspondence 243
- 6.5 Species diversity 247
1 – Diversity, 250; 2 – Evenness, equitability, 255; 3 – Species diversity through space, 258
- 6.6 Software 264

7. Ecological resemblance

- 7.0 The basis for clustering and ordination 265
- 7.1 Q and R analyses 266
- 7.2 Association coefficients 269
1 – Similarity, distance, and dependence coefficients, 270; 2 – The double-zero problem, 271
- 7.3 Q mode: similarity coefficients 273
1 – Symmetrical binary coefficients, 273; 2 – Asymmetrical binary coefficients, 275; 3 – Symmetrical quantitative coefficients, 278; 4 – Asymmetrical quantitative coefficients, 284; 5 – Probabilistic coefficients, 288
- 7.4 Q mode: distance coefficients 295
1 – Metric distances, 299; 2 – Semimetrics, 310
- 7.5 R mode: coefficients of dependence 313
1 – Descriptors other than species abundances, 313; 2 – Species abundances: biological associations, 316
- 7.6 Choice of a coefficient 320
- 7.7 Transformations for community composition data 327
1 – Transformation formulas, 328; 2 – Numerical example, 332; 3 – Beals smoothing, 334
- 7.8 Software 334

8. Cluster analysis

- 8.0 A search for discontinuities 337
- 8.1 Definitions 338

8.2	The basic model: single linkage clustering	341
8.3	Cophenetic matrix and ultrametric property	346
	<i>1 – Cophenetic matrix, 346; 2 – Ultrametric property, 347</i>	
8.4	The panoply of methods	347
	<i>1 – Sequential versus simultaneous algorithms, 347; 2 – Agglomeration versus division, 348; 3 – Monothetic versus polythetic methods, 348; 4 – Hierarchical versus non-hierarchical methods, 348; 5 – Constrained clustering methods, 349; 6 – Probabilistic versus non-probabilistic methods, 349</i>	
8.5	Hierarchical agglomerative clustering	350
	<i>1 – Single linkage agglomerative clustering, 350; 2 – Complete linkage agglomerative clustering, 350; 3 – Intermediate linkage clustering, 351; 4 – Unweighted arithmetic average clustering (UPGMA), 352; 5 – Weighted arithmetic average clustering (WPGMA), 355; 6 – Unweighted centroid clustering (UPGMC), 357; 7 – Weighted centroid clustering (WPGMC), 360; 8 – Ward's minimum variance method, 360; 9 – General agglomerative clustering model, 367; 10 – Flexible clustering, 370; 11 – Information analysis, 372</i>	
8.6	Reversals	376
8.7	Hierarchical divisive clustering	377
	<i>1 – Monothetic methods, 377; 2 – Polythetic methods, 379; 3 – Division in ordination space, 380; 4 – TWINSpan, 381</i>	
8.8	Partitioning by <i>K</i> -means	383
8.9	Species clustering: biological associations	389
	<i>1 – Non-hierarchical complete linkage clustering, 392; 2 – Concordance analysis, 395; 3 – Indicator species, 397</i>	
8.10	Seriation	403
8.11	Multivariate regression trees (MRT)	406
8.12	Clustering statistics	411
	<i>1 – Connectedness and isolation, 411; 2 – Cophenetic correlation and related measures, 412</i>	
8.13	Cluster validation	415
8.14	Cluster representation and choice of a method	418
8.15	Software	423
9.	Ordination in reduced space	
9.0	Projecting data sets in a few dimensions	425
9.1	Principal component analysis (PCA)	429
	<i>1 – Computing the eigenvectors of a dispersion matrix, 431; 2 – Computing and representing the principal components, 432; 3 – Contributions of the descriptors, 434; 4 – PCA biplots, 443; 5 – Principal components of a correlation matrix, 445; 6 – The meaningful components, 448; 7 – Misuses of principal component analysis, 450; 8 – Ecological applications, 452; 9 – Algorithms, 456; 10 – Metric ordination of community composition data, 462</i>	

- 9.2 Correspondence analysis (CA) 464
 - 1 – Computation, 466; 2 – Numerical example, 471; 3 – Interpretation, 476; 4 – Site $\times$ species data tables, 477; 5 – Arch effect and detrended correspondence analysis, 482; 6 – Ecological applications, 487; 7 – Algorithms, 490*
- 9.3 Principal coordinate analysis (PCoA) 492
 - 1 – Computation, 493; 2 – Numerical example, 494; 3 – Rationale of the method, 497; 4 – Negative eigenvalues, 500; 5 – Ecological applications, 506; 6 – Algorithm, 511*
- 9.4 Nonmetric multidimensional scaling (nMDS) 512
- 9.5 Software 519

10. Interpretation of ecological structures

- 10.0 Ecological structures 521
- 10.1 Clustering and ordination 522
- 10.2 The mathematics of ecological interpretation 526
 - 1 – Explaining ecological structures, 530; 2 – Forecasting ecological structures, 532; 3 – Ecological prediction, 534*
- 10.3 Regression 536
 - 1 – Simple linear regression: model I, 539; 2 – Simple linear regression: model II, 543; 3 – Multiple linear regression, 555; 4 – Polynomial regression, 568; 5 – Partial linear regression and variation partitioning, 570; 6 – Nonlinear regression, 583; 7 – Logistic regression, 584; 8 – Splines and LOWESS smoothing, 589*
- 10.4 Path analysis 592
- 10.5 Matrix comparisons 597
 - 1 – Two association matrices: Mantel test, 598; 2 – More than two association matrices, 604; 3 – ANOSIM test, 608; 4 – Procrustes test, 611*
- 10.6 The fourth-corner problem 613
 - 1 – Comparing two qualitative variables, 614; 2 – Test of statistical significance, 616; 3 – Permutational models, 618; 4 – Other types of comparisons among variables, 621*
- 10.7 Software 622

11. Canonical analysis

- 11.0 Principles of canonical analysis 625
- 11.1 Redundancy analysis (RDA) 629
 - 1 – Simple RDA, 630; 2 – Statistics in simple RDA, 632; 3 – The algebra of simple RDA, 635; 4 – Numerical examples, simple RDA, 642; 5 – RDA and CCA of community composition data, 646; 6 – Partial RDA, 649; 7 – Statistics in partial RDA, 651; 8 – Tests of significance in partial RDA, 651; 9 – Numerical example, partial RDA, 653; 10 – Some applications of partial RDA, 654; 11 – Variation partitioning by RDA, 658*

- 11.2 Canonical correspondence analysis (CCA) 661
 - 1 – The algebra of canonical correspondence analysis, 662; 2 – Numerical example, 667*
- 11.3 Linear discriminant analysis (LDA) 673
 - 1 – The algebra of discriminant analysis, 676; 2 – Statistics in linear discriminant analysis, 682; 3 – Numerical example, 683*
- 11.4 Canonical correlation analysis (CCorA) 690
 - 1 – The algebra of canonical correlation analysis, 691; 2 – Statistics in canonical correlation analysis, 694; 3 – Applications of CCorA, 694*
- 11.5 Co-inertia (CoIA) and Procrustes (Proc) analyses 696
 - 1 – The algebra of co-inertia analysis (CoIA), 697; 2 – Symmetric Procrustes analysis (Proc), 703; 3 – Canonical correlation, Procrustes, or co-inertia analysis? 705*
- 11.6 Canonical analysis of community composition data 706
- 11.7 Software 709

12. Ecological data series

- 12.0 Ecological series 711
- 12.1 Characteristics of data series and research objectives 714
- 12.2 Trend extraction and numerical filters 722
- 12.3 Periodic variability: correlogram 727
 - 1 – Autocovariance and autocorrelation, 728; 2 – Cross-covariance and cross-correlation, 735*
- 12.4 Periodic variability: periodogram 739
 - 1 – Periodogram of Whittaker and Robinson, 739; 2 – Contingency periodogram of Legendre et al., 744; 3 – Periodogram of Schuster, 747; 4 – Periodogram of Dutilleul, 751; 5 – Harmonic regression, 753*
- 12.5 Periodic variability: spectral and wavelet analyses 754
 - 1 – Series of a single variable, 754; 2 – Multidimensional series, 759; 3 – Maximum entropy spectral analysis, 763; 4 – Wavelet analysis, 766*
- 12.6 Detection of discontinuities in multivariate series 768
 - 1 – Ordinations in reduced space, 768; 2 – Segmenting data series, 769; 3 – Webster's method, 770; 4 – Time-constrained clustering by MRT, 773; 5 – Chronological clustering, 773*
- 12.7 Box-Jenkins models 780
- 12.8 Software 782

13. Spatial analysis

13.0 Spatial patterns 785

13.1 Structure functions 792

1 – Spatial correlograms, 793; 2 – Interpretation of all-directional correlograms, 800; 3 – Variogram, 807; 4 – Multivariate variogram, 813; 5 – Spatial covariance, semi-variance, correlation, cross-correlation, 816; 6 – Multivariate Mantel correlogram, 819

13.2 Maps 821

1 – Trend-surface analysis, 822; 2 – Interpolated maps, 829; 3 – Measures of fit, 833

13.3 Patches and boundaries 834

1 – Connection networks, 834; 2 – Space-constrained clustering, 839; 3 – Ecological boundaries, 844; 4 – Dispersal, 847

13.4 Unconstrained and constrained ordination maps 849

13.5 Spatial modelling through canonical analysis 852

13.6 Software 857

14. Multiscale analysis: spatial eigenfunctions

14.0 Introduction to multiscale analysis 859

14.1 Distance-based Moran's eigenvector maps (dbMEM) 861

1 – Algorithm, 862; 2 – Numerical examples, 864; 3 – Ecological applications, 869; 4 – Interpretation of the fractions, 877

14.2 Moran's eigenvector maps (MEM), general form 881

1 – Algorithm described through an example, 881; 2 – Different types of MEM eigenfunctions, 884

14.3 Asymmetric eigenvector maps (AEM) 888

1 – Algorithm described through an example, 888; 2 – Ecological applications, 892

14.4 Multiscale ordination (MSO) 894

14.5 Other eigenfunction-based methods of spatial analysis 900

1 – Space-time interaction, 900; 2 – Multiscale codependence analysis, 901; 3 – Estimating and controlling for spatial structure in modelling, 902

14.6 Multiscale analysis of beta diversity 903

14.7 Software 904

References 907

References to cited works, 907

References to R packages, 963

Subject index 969