Index

accelerated bootstrap 26 adaptive sampling 157 added variance component 188 additivity and transformations 67, 280 adjusted r² 137 adjusted univariate F tests 282-3, 319 adjusting significance levels 49-50 agglomerative hierarchical clustering 489-91 Akaike information criterion (AIC) 139, 370-1 alternative hypothesis 33-4 analysis of covariance (ANCOVA) 339 assumptions 348-9 comparing ANCOVA models 348 covariate values similar across groups 349 designs with two or more covariates 353-4 factorial designs 354-5 heterogeneous slopes 349 comparing regression lines 352 dealing with heterogeneous within group regression slopes 350-2 Johnson-Neyman procedure, Wilcox modification 350-1 testing for homogeneous within group regression slopes 349-50 linear effects model 342-6 nested designs with one covariate 355-6 null hypotheses 347-8 partly nested models with one covariate 256-7 robust 352-3 single factor 339-48 specific comparison of adjusted means 353 analysis of deviance 399-400 analysis of similarities (ANOSIM) 484-5 analysis of variance (ANOVA) diagnostics 194-5 factorial designs 230-2 linear effects model 178-84, 210-13, 225-30 multifactor 208-61

multiple linear regression 119-21 multivariate see multivariate analysis of variance (MANOVA) nested (hierarchical) designs 214-15 partly nested designs 313-15 presentation of results 496 randomized complete block designs 272-3 robust 195-6 simple linear regression 88-9 single factor (one way) designs 173-88, 191-5, 204-7 specific comparisons of means 196-201 testing equality of group variances 203 - 4tests for trends 202-3 ANCOVA see analysis of covariance angular transformations 66 ANOVA see analysis of variance arbitrary significance levels 53 arcsin transformation 66 association matrix choice in principal components analysis 451-2 decomposition 449-50 audiovisual aids 507-9 axis rotation, principal components analysis 447-9 backward variable selection 139-40 bar graphs 500-2 Bayes Theorem 9, 54 Bayesian inference 27-31, 54-7 likelihood function 28, 54-5 posterior probability 28-9, 54-7 prior knowledge and probability 28 Bayesian information criterion (BIC) 139 beta distribution 11 bias-corrected bootstrap 26 binary variables, dissimilarity measures 413

binomial distribution 11 biological population 14 biological significance 44 biplots 456 bivariate normal distribution 72-3 block designs

crossover designs 296-8 factorial randomized block designs 290 - 2generalized randomized block designs 298 incomplete block designs 292 Latin square designs 292-6 randomized complete block (RCB) designs 262-90 blocking, efficiency of 285-6 blocking factor, time as 287 Bonferroni procedure 49-50 bootstrap estimator 25-6 Box-Cox family of transformations 66 boxplots 60-1 Bray-Curtis dissimilarity 413, 483-5

Canberra distance 413 canonical correlation analysis 463-6 canonical correspondence analysis (CCA) 467-8, 492 categorical data analyses 380-400 categorical predictors linear regression 135-7 logistic regression 368, 371 cell plots factorial design 251 randomized complete block design 277 censored data 69-70 comparing two or more populations 70-1 estimation of mean and variance 70 center of distribution 15-16 centering variables 67 Central Limit Theorem 18, 20 central t distribution 36 centroid 402 chi-square (χ^2) distribution 12–13, 20-1, 38 chi-square (χ^2) statistic 380, 388 chi-square dissimilarity 413 City block distance 412-13 classical scaling 474-6 classical statistical hypothesis testing 32-4 classification analysis 488 cluster analysis 488-91 discriminant function analysis 435-41

INDEX 528

classification functions, discriminant analysis 440 cluster analysis 488-9 agglomerative hierarchical clustering 489-91 and scaling 491-2 divisive hierarchical clustering 491 non-hierarchical clustering 491 cluster sampling 156 coefficient of determination (r^2) 91–2, 122 coefficient of variation (CV) 16-17 coefficients of linear combination 432-3 Cohen's effect size 190-1 collinearity 127 dealing with 129-30 detecting 127-9 combining *P* values 50 combining results from statistical tests 50-1 common population parameters and sample statistics 15-16 complete independence, three way contingency tables 393 completely randomized (CR) designs 173 comparison with randomized complete block 286 complex factorial designs 255-7 compound symmetry assumption 281-2 conditional independence and odds ratios, three way contingency tables 389-93 conditional probabilities 9 confidence intervals population mean 19-20 regression line 87 variances 22-3, 189 confidence regions, regression 76-7 confounding, experimental design 157 - 60constrained ordinations 469-70, 492 contingency tables 381 analysis using log-linear models 393-400 three way tables 388-93, 395-400 two way tables 381-8, 394-5 continuous variables 7 dissimilarity measures for 412-13 probability distributions of 9-10 contrast-contrast interactions 254 controls 160-1 Cook's D statistic 68, 95

correlated data models 375-6 generalized estimating equations 377 - 8multi-level (random effects) models 376-7 correlation analysis 72 parametric and non-parametric confidence regions 76-7 parametric correlation model 73-6 power of tests 109-10 relationship with linear regression 106 robust correlation 76 correlation coefficient 72, 102 and regression slope 106 Kendall's (τ) 76 Pearson's (r) 74-5 Spearman's rank (r_s) 76 correlation matrix 403, 405 correspondence analysis 459 canonical 467-8, 469-70 detrended 463 mechanics 459-60 reciprocal averaging 462 scaling and joint plots 461-2 use with ecological data 462-3 covariances and correlation 73-5 assumption for randomized complete block, repeated measures and split-plot ANOVA models 281-2, 318 crossover designs 296-8 data standardization, multivariate analysis 415-17 decision errors asymmetry and scalable decision criteria 44-5 Type I and II errors 42-4 deductive reasoning 2

degrees of freedom (df) 19-20, 22 deleted residuals 95 dendrograms 488-9 detrended correspondence analysis (DCA) 463 diagnostic graphics multiple linear regression 125-6 simple linear regression 96-8 dichotomous variables, dissimilarity measures for 413 discrete variables 7 discriminant function analysis 435 assumptions 441

estimation

classification and prediction 439-40 description and hypothesis testing 437-9 more complex designs 441 versus MANOVA 441 displaying summaries of data 498-500 dissimilarity matrices, comparing 414-15 dissimilarity measures binary variables 413 comparison 414 continuous variables 412-13 mixed variables 413-14 testing hypotheses about groups of objects (M)ANOVA based on axis scores 483 analysis of similarities (ANOSIM) 484-5 distance-based redundancy analysis 485 MANOVA based on original variables 483 Mantel test 483 multi-response permutation procedures 483-4 non-parametric MANOVA 485-7 distance-based redundancy analysis 485 distance matrices, comparing 414-15 distance measures 409, 412-13 divisive hierarchical clustering 491 Dixon's Q test 68 dotplots 60 dummy variables 135-7 Duncan's Multiple Range test 200 Dunn-Sidak procedure 50 Dunnett's test 201 eigenvalue equality 452-3 eigenvalues 128-9, 405-6, 450, 452, 454 eigenvectors 406-9, 450-1, 461-2 empiric models 2 enhanced multidimensional scaling convergence problems 482 enhanced algorithm 476-8 interpretation of final configuration 478, 481-2 stress 477 error bars 504-6 alternative approaches 506-7

INDEX | 529

methods for 23-5 resampling methods 25-7 types of 15 Euclidean distance 412, 475, 483 examples (see also examples, worked) aphids, effects of tree species and time on abundance 306, 315 barnacle larvae, effects of copper 159-60 bats, dependence on area and woodland disturbance 401-2 beavers, effect on aquatic geochemistry 443-4 benthic invertebrates, effects of fish 161-2 birds spatial variation in Wisconsin counts 265 species richness and habitat variables 142 caddisflies, effects of competition and hydroperiod on body mass and survival 303, 309, 315 caterpillar, effects of sex, population, and temperature on growth 255 cladocerans, effects of kairomones and body mass on morphology 339 copepods grazing on dinoflagellates 4-5 coral reef fish, variation in recruitment 209-12 crayfish, hormone levels in 157 elephant seals, association between survival and mating success 382-5 eutrophication in lakes 8 fir trees, growth in response to N and P 252-4 fish, similarity of fish assemblages between sites 476 floral diversity, correlation between floral similarity and intensity of sampling 415 fossil invertebrates, effect of salinity, lake level and swamp development on community structure 466 frogs, contribution of survivorship, size, and larval period to separation of species 441 grassland plants, competition among 245-6 intertidal algae

variation in recruitment on rocky shores 208-9 intertidal molluscs, effects of harvesting on abundance 167 Jerusalem Artichoke, effects of inflorescence removal on asexual investment 303 leaf miners, effects of leaf damage on mortality 263 limpets distribution on rocky shores 65-6 effect of enclosure size on growth 208 effects of intraspecific competition on growth 198 marine invertebrates, larval settlement in response to microbial films 37 marsh plants, effects of herbivores and nutrients on densities 335-6 mayfly larvae, life history responses to predation and food reduction 425 mussels and barnacles, effects of flow and tidal height 302-3 oysters, variation in abundance through mangrove forests 224 - 5perennial herb effects of flower position on fruit and seed production 223 effects of leaf damage and flowering order on floral traits 340 effects of plant diversity and physicochemical variables on presence of exotic species 365 phytoplankton, effects of sewage 159-60 plants, effects of fire 158-60 rainforest seedlings, effects of land crabs and light gaps on recruitment 332-4 rodents effects of illumination and seed distribution on seed consumption 332-4 effects of predation and time on survival 332-4 salamanders competition between 160-2 effects of density and initial size

effects of herbivore removals 322

on larval growth and metamorphosis 290 effects of invertebrate food level and tadpole presence on growth 222 sawfly larvae, effect of sawfly species and trees on foraging behavior 223, 229, 236 seastars, effects of mussel recruitment on abundance 263 seed availability, effects of microsite and time 328-31 smallmouth bass, relationship between nests and habitat variables 145 squirrels, effect of food abundance, age, and reproductive history on breeding success 374-5 stream insects, spatial variation in density 219 trees effects of light and seedling height on sapling growth 222, 240 effects of temperature on respiration rates 305, 309 variation in leaf structure 219 turtles, dependence of growth rate on sex, site, and year 375 understory plants, effects of competition on hummingbird visits and seed production 296 - 7warblers, contribution of vegetation attributes to habitat discrimination 440 weevil parasitoids on alfalfa plants, effects of honeydew 263-4, 329 - 31wildlife underpasses, effectiveness in relationship to human activity 401-9 examples, worked abalone, abundance in marine protected areas 165-6 annual plants, effects of temperature, CO₂, and biomass on developmental age 354 ants, effects of predators, soil type and light level on colony size and herbivory of host plants 328 - 9beetles, effects of experimental fire on community structure 468

530 | INDEX

examples, worked (cont.) birds abundances in different kinds of forest patches 111, 115-7, 121-2, 124-7, 132, 135-41, 145-9, 372-4 characterization of assemblages in forests 447-55, 474, 478-82, 486-91 effects of eucalypt flowering on forest bird communities 322-6 Cane toads, responses to hypoxia 306-10, 321, 356 chemistry of forested watersheds 21-3, 31-2, 60, 62-3, 66-9, 401, 420, 444-53, 463-4 coarse woody debris in lakes, relationship with tree density and other habitat variables 78-91, 100-3 Coolibah trees, occurrence of dead trees in different sections of floodplain 382-7, 394 copepod larvae, effects of food and sibships on age at metamorphosis 223, 258-9 diatoms, effects of heavy metals in rivers 173-83, 206-7 flying squirrels, effects of logging and time on age structure 388-93, 398-9 frogs in burned and unburned catchments 266-74, 278-9, 281 - 8fruitflies, effects of number and types of mating partners on longevity 340-7 heavy metals in marine sediments, differences between locations 426-39 land crabs on Christmas Island, relationship to burrow density 72-6, 447-50 leaf morphology of plants, variation among functional groups and ecosystems 243, 401-23, 426, 429-30, 435-40 limpets effects of season and adult density on fecundity 223-36, 241, 251-4 effects of trampling on abundance 303-5, 310-15 variation in abundance on oyster

shells attached to mangroves 225-37, 253-4, 256-7 marine invertebrates abundance in response to nutrients 242-7 recruitment of polychaetes in response to microbial films 176-81, 198, 202, 205, 497-9 species richness in mussel clumps 78-84, 94-8, 104-5, 108, 151 mites, effects of leaf domatia on abundance 264-76, 283, 299 mussels, effects of crab predation, location and size on attachment strength 355-6 oldfield insects, effects of habitat fragmentation on richness 293 - 5palm seedling, survivorship in different successional zones 240-1 perennial shrub, effects of herbivory and plant size on fruit production 357-8 plant functional groups, relationship between abundance and habitat variables 111-14, 118-21, 124-7, 130, 135, 153 plant regeneration after fire, comparison of ant and vertebrate dispersal 382-7 plant reproduction, effects of clipping and emasculation on flower, fruit, and seed production 435 pond invertebrates, effects of hydroperiod and predation 254-5 predatory gastropods, fecundity 38-9, 45, 61 rare plants, relationship between genetic and geographic distances 414, 478-9, 488-90 rodents effects of distance to canyon, habitat fragmentation and vegetation cover on presence 365-8, 447-55, 460-1, 467-71, 474-81 effects of habitat type and location on abundance 327-8 saltmarsh plants, effects of

parasites, patch size, and zone on biomass 435 sea urchins effects of food and initial size on inter-radial sutures 340-7, 350 effects of grazing 209-20 seabirds, energy budgets when breeding 38, 40, 61 species richness, association between local and regional 133-4 spiders effect of lighting on web structure 38, 41 effects of density and predator reduction on spiderling growth 290-2 effects of predation by lizards and scorpions on presence/absence 360-3 wildebeest carcasses, crossclassification by sex, predation and health 388-93, 395-9 Expectation-Maximization (EM) algorithm and missing data 421-3 experimental design 157-64 controls 160-1 efficiency of blocking 285-6 independence 163 power analysis 166-8 problem of confounding 157-60 randomization 161-3 reducing unexplained variance 164 replication 158-60 experiments and other tests 5-7 exploratory data analysis 58-62 exponential distribution 11 F distribution 12-13, 186, 188 F-ratio statistic 38-9, 204 F-ratio test 42 single factor ANOVA 186-7 factorial ANOVA 235-6, 237 nested ANOVA 215-16 partly nested ANOVA 315-18 randomized complete block and repeated measures ANOVA 274 factor analysis 458-9 factor effects 188

factor effects 188 factorial models 247–9 fixed effects 190–1 nested models 216–18 random effects 188–90

INDEX | 531

factorial designs analysis of covariance 354-5 analysis of variance 230-2 assumptions 249-50 comparing ANOVA models 241 complex designs 255-7 factor effects 247-9 fractional designs 257-8 interpreting interactions exploring interactions 251-2 simple main effects 252-4 unplanned multiple comparison 252 linear models 225-30 mixed factorial and nested designs 258 - 9null hypotheses 232-7 power analysis 259-60 relationship with nested design 261 robust 250 specific comparisons on main effects 250-1 unbalanced designs 241-7 factorial randomized block designs 290 - 1falsification 2-3 alternatives to 4-5 field experiments 6 Fisherian hypothesis testing 33-4 Fisher's Protected Least Significant Difference test (LSD test) 200 fixed X assumption, regression 94 fixed covariate (X), ANCOVA models 349 fixed effects 190-1 fixed effects models 176-7 factorial designs 232-6, 237-40 forward variable selection 139 fourth root transformations 65 fractional factorial designs 223, 257 - 8frequency analyses 380-400 G² statistic 364, 367, 388 gamma distribution 11 Gauss-Newton algorithm 151-2 Gaussian distribution 10 generalized additive models (GAMs)

372–5, 379 generalized estimating equations (GEEs) 377–9 generalized linear models (GLMs) 77–8, 359–60, 378–9 logistic regression 360–71

Poisson regression 371-2 generalized randomized block designs 298 goodness-of-fit, logistic regression 368-70 goodness-of-fit tests, single variable 381 graphical displays 58–62 assumptions of parametric linear models 62-4 principles 499 types of 500-4 graphics packages 508 working with color 508-9 group effects for a fixed factor 190-1 group means, specific comparisons of 196-201 group variances, testing equality of 203 - 4

Hampel M-estimator 16 hierarchical partitioning 141-2 histograms 59-60 Hodges-Lehmann estimator 16 Hosmer-Lemeshow statistic 369 Hotelling-Lawley trace 431 Huber M-estimator 16 hybrid multidimensional scaling 478 hybrid statistical hypothesis testing 34 hypotheses 3-4 hypothesis testing 32-57 Bayesian 54-7 statistical 32-54 hypothesis tests for a single population 35-6 for two populations 37-9 imputation (missing observations)

420-1 incomplete block designs 292 independence, experimental design 163 independence assumption factorial ANOVA models 249 linear models 64 linear regression models 93-4 nested ANOVA models 218 randomized complete block and repeated measures ANOVA models 280 single factor ANOVA models 193-4 indicator variables 135-7 inductive reasoning 2 influence

multiple regression 125 simple regression 95-6 interactions in factorial designs 251 - 2simple main effects 252-4 treatment-contrast and contrast-contrast interactions 254-5 interactions in multiple regression 130-1 probing interactions 131-3 interactions in partly nested designs 321 interactions in randomized complete block designs treatment by block interactions 274-7 unreplicated designs 277-80 intercept 87 interquartile range 17 interval estimates 15

jackknife estimator 26–7 jackknifed classification function 440 Johnson–Neyman procedure, Wilcox modification 350–1 joint plots, correspondence analysis 461–2

Kendall's correlation coefficient (τ) 76 kernel estimation 59–60 kernels (smoothing) 108–9 Kolmogorov–Smirnov (K–S) test 381 Kruskal–Wallis test 195–6 Kruskal's stress 477 Kuhnian approach to scientific method 4 Kulczynski dissimilarity 413 KYST algorithm 476–7

L-estimators 15 laboratory experiments 6 Lakotsian approach to scientific method 4 Latin square designs 292–6 layout of tables 497–8 least absolute deviations (LAD) 104–5 leverage 194 multiple regression 125 simple regression 95–6 likelihood functions 28, 54–5 likelihood inference 52 likelihood principle 52 likelihood ratio statistic 364 line graphs 502

532 | INDEX

linear combinations of variables, multivariate analysis 405-6 linear effects model nested designs 210-13 partly nested designs 310-13 randomized complete block (RCB) designs 269-71 single factor ANCOVA designs 342-6 single factor designs 178-84 linear models 77-8 ANCOVA models 342-7 assumptions homogeneity of variances 63 independence 64 linearity 64 normality 62-3 definition 77 factorial ANOVA models 225, 227-230 fixed effects ANOVA models 176-7 multiple regression 114, 117-19 nested ANOVA models 210-14 partly nested ANOVA models 310-13 presentation of results 494-7 random effects ANOVA models 176 - 7randomized complete block and repeated measures ANOVA models 268-72 simple regression 80, 82-7 single factor ANOVA models 178-81. 183-4 linear models for factorial designs 225 - 7model 1 - both factors fixed 227-9 model 2 - both factors random 229 model 3 - one factor fixed and one factor random 229-30 linear regression analysis 78 analysis of variance 88-9 assumptions 92 fixed X 94 homogeneity of variance 93 independence 93-4 normality 92-3 linear model for regression 81-5 null hypotheses 89–90 power analysis 109-10 presentation of results 493-6 relationship with correlation 106 residual plots 96-8 robust regression 104-6 scatterplots 96-7

simple linear regression 78-82 transformations 98 weighted least squares 99-100 variance explained 91-2 (see also multiple linear regression analysis) linear regression diagnostics 94-5 influence 95-6 leverage 95-6 residuals 87, 95-6 linear regression models 81-5 comparing models 90-1 diagnostic graphics 96-8 estimating model parameters 85 confidence intervals 87 intercept 87 predicted values and residuals 87 slope 85-6 standardized regression slope 86 Model II regression 100-4 regression through the origin 98-9 (see also multiple linear regression models) linearity, and transformations 67 linearity assumption linear models 64 single factor ANCOVA 348-9 link function, generalized linear models 359-60 loadings, MANOVAs 433 locally weighted regression scatterplot smoothing 107-8 log-linear models 393-4 complex tables 400 three way tables 395 analysis of deviance tables 399-400 full and reduced models 395-8 test for complete independence 399-400 testing and interpreting two way interactions 398-9 tests for three way interactions 398 two way tables full and reduced models 394 test for independence 394-5 logistic regression 360 assumptions 368 categorical predictors 368 multiple 365-8 simple 360-5 software 371 logistic regression models

goodness-of-fit and residuals 368-70 model diagnostics 370 model selection 370-1 lognormal distributions 11, 65 Lo(w)ess smoothing 107-8 M-estimators 15-16 regression 105-6 main effects factorial designs 237-41, 250-1, 252-4 partly nested designs 320-1 major axis (MA) regression 101-2 Mallow's C_n 137 Manhattan distance 412-13 manipulative experiments 5-6 Mann-Whitney-Wilcoxon test 47-8 MANOVA see multivariate analysis of variance Mantel test 483 marginal independence and odds ratios, three way contingency tables 393 Mauchley's test 284 Maximum Likelihood (ML) estimation 23 - 4.190and Expectation-Maximization (EM) algorithm 421-3 and linear regression model 90 nonlinear regression modeling 150, 152 versus OLS estimation 25 maximum norm quadratic unbiased estimation (MINQUE) 190 mean 10, 16 means, specific comparisons of 196-201 median 10, 15-16 median absolute deviation (MAD) 16 - 17meta-analysis 50–1 Minkowski distance 413 missing cells, factorial designs 244-7 missing observations 68-9 deletion 420 imputation 420-1 maximum likelihood and EM 421 - 3multiple regression analysis 143 multivariate data sets 419-20 principal components analysis 454 mixed effects models, factorial designs 236-7, 240-1

mixed factorial and nested designs 258-9 mixed linear models 223 mixed variables, general dissimilarity measures 413-14 mode 10 Model I regression see linear regression analysis; linear regression models Model II regression 100-4, 142-3 models 2-3 multidimensional scaling (MDS) 473-4, 492 classical 474-6 enhanced 476-82 principal coordinates analysis (PCoA) 474-6 relating to covariates 487-8 relating to original variables 487 multifactor analysis of variance (ANOVA) 208 factorial designs 221-60 nested (hierarchical) designs 208 - 21pooling in multifactor designs 260-1 presentation of results 496-7 relationship between factorial and nested designs 261 multi-level (random effects) models 376 - 7multimodal distributions 63 multinomial distribution 11 multiple linear regression analysis 111 analysis of variance 119-21 assumptions 125 collinearity 127-30 diagnostic graphics 125-6 finding the "best" regression model 137 criteria for "best model" 137-9 selection procedures 139-41 hierarchical partitioning 141-2 indicator (dummy) variables 135-7 interactions 130-3 missing data 143 null hypotheses 121 power analysis 143 relative importance of predictor variables 122 change in explained variation 123 standardized partial regression slopes 123-4 tests on partial regression slopes 122-3

residual plots 126 robust regression 143 scatterplots 125-6 transformations 127 variable selection 137-41 variance explained 122 weighted least squares 142 (see also polynomial regression) multiple linear regression diagnostics 125 influence 125 leverage 125 residuals 125 multiple linear regression models 114, 118-19 estimating model parameters 119 Model II regression 142-3 model comparisons 121-2 regression through the origin 142 multiple logistic regression 365-7 logistic model and parameters 367-8 multiple testing adjusting significance levels and/or P values 49-50 and increased probability of Type I errors 48-9 multi-response permutation procedures 483-4 multivariate analysis derivation of components 409 eigenvalues 405-6 eigenvectors 406-9 linear combinations of variables 405 standardization, association and dissimilarity 417 multivariate analysis of variance (MANOVA) 283-4, 319, 425-35 and statistical software 433 assumptions 433-4 complex designs 434-5 multidimensional scaling 483 non-parametric 485-7 presentation of results 496-7 relationship to principal components analysis 437 relative importance of each response variable 432-3 robust 434 single factor 426-32 specific comparisons 432 versus discriminant function analysis 441 multivariate data 400-1

standardizations 415-17 multivariate data sets, screening 418-23 multivariate dissimilarity measures 410-12, 417 comparison 414 for continuous variables 412-13 for dichotomous (binary) variables 413 for mixed variables 413-14 multivariate distance measures 409, 412-13 multivariate distributions and associations 402-4, 417 multivariate graphics 417-18 multivariate outliers 419 multivariate plots 62 negative binomial distribution 12 nested (hierarchical) designs 208-10 analysis of covariance 355-6 analysis of variance 214-15 assumptions 218 comparing ANOVA models 216 factor effects 216-18 linear models for nested analyses 210 - 14more complex designs 219 null hypotheses 215-16 power analysis 219-21 relationship with factorial design 261 specific comparisons 219 unequal sample sizes 216 (see also partly nested designs) Neyman-Pearson hypothesis testing 33-4 no-intercept regression model 99 non-hierarchical clustering 491 nonlinear models 150-2 nonlinear regression modeling 150-1 non-parametric confidence regions 76 - 7non-parametric density estimation 59 non-parametric MANOVA 485-7 non-parametric tests, rank-based 46-8 normal distribution 10, 17-18 normality assumption ANCOVA models 348 factorial ANOVA models 249 linear models 62-3 linear regression models 92-3 nested ANOVA models 218 partly nested ANOVA models 318 principal components analysis 454

534 | INDEX

normality assumption (cont.) randomized complete block and repeated measures ANOVA models 280 single factor ANOVA models 192 null hypothesis 3-4, 32-3, 37 always false 53 contingency tables 385-6, 394-5 factorial ANOVA 232-7 linear regression analysis 89-90 multiple linear regression analysis 121 nested ANOVA 215-16 partly nested ANOVA 315-18 randomized complete block and repeated measures ANOVA 273-4 simple logistic regression 363-4 single factor ANCOVA 347-8 single factor ANOVA 186-7 single factor MANOVA 430-2 single population 35-6 two populations 37-9 observation uncertainty 7 observations 7, 14 odds ratios and conditional independence, three way contingency tables 389-93 and marginal independence, three way contingency tables 393 two way contingency tables 386-7 omega squared 190-1 one-sample t test 35-6 one-tailed tests 37 oral presentations 507 graphics packages 508–9 information content of figures 509 scanned images 509 slides, computers or overheads 507 - 8ordinary least squares (OLS) estimation 26 linear regression model 85-6, 90, 101-3, 107 nonlinear regression modeling 150, 152 versus ML estimation 25 ordination and clustering for biological data 491 - 2constrained 469-70 partial 471

principal components analysis 454-6 scaling 418, 454-6, 461-3, 481, 491-2 outliers 60, 68, 96, 194-5, 419 P values 40, 46, 52 adjusting 49-50 as measure of evidence 53 combining 50 difference with Bayesian posterior probabilities 56 tests based on adjusting 201 parameters 14 parametric confidence regions 76-7 parametric correlation model 73-4 assumptions 75-6 covariance and correlation 73-5 hypothesis tests for r 75 parametric linear models, assumptions 62-4 parametric tests assumptions 39-42 robust 45 versus non-parametric tests 46-8 partial ordination 471 partial regression slopes 118-19, 122 - 3standardized 123-4 partly nested designs analysis 309-18 analysis of covariance 356-7 analysis of variance 313-15 and statistical software 335-7 assumptions between plots/subjects 318 within plots/subjects and multisample sphericity 318-20 comparing ANOVA models 318 complex designs 323-4, 335 additional betweenplots/subjects and withinplots/subjects factors 332-5 additional betweenplots/subjects factors 324-9 additional within-plots/subjects factors 329-32 interactions 321 linear effects model 310-13 main effects 320-1 null hypotheses 315-18 power analysis 323 profile analysis 319, 321-2 reasons for use 309 recommended strategy 319-20

repeated measures designs 305-9 robust 320 split-plot designs 301-5 unbalanced 322-3 with one covariate 356-7 path analysis 145-9 pattern description 2 PCA see principal components analysis PCoA see principal coordinates analysis Pearson's correlation coefficient (r) 74-5 Peritz's test 201 pie charts 503-5 Pillai trace 431 planned comparisons or contrasts 197-8 partitioning SS 198-9 planned contrasts among adjusted means, ANCOVA 353 point estimates 15 Poisson distribution 10-12 Poisson regression 371-2, 379 polynomial regression 133-5 pooling in multifactor designs 260-1 Popperian falsificationism 2-4, 32 population mean, confidence intervals 19-20 population parameters 14-15 population range 16 population standard deviation 17 population variance 16 populations 14 posterior probabilities 9, 28–9, 54–7 power analysis 164-6 correlation 109-10 effect size 168-70 environmental monitoring special case 170 specifying 169 factorial ANOVA 259-60 linear regression 109-10 multiple linear regression 143 nested ANOVA 219-21 partly nested ANOVA 323 post hoc power calculation 168 randomized complete block and repeated measures ANOVA 289-90 single factor ANOVA 204-6 use in experimental design 166 effect size 166-7 sample size calculation 166 sequence for using power

analysis to design experiments

167-8 using 170-1 power transformations 65-6 predicted (fitted) values contingency tables 385, 387 factorial ANOVA model 230 linear regression model 87 logistic regression 369-370 multiple regression model 119 nested ANOVA model 213-14 partly nested ANOVA model 313 randomized complete block and repeated measures ANOVA model 271 single factor ANCOVA model 347 single factor ANOVA model 184 predictor variables 77-8, 128, 176-7, 370 presentations displaying summaries of data 498-506 error bars 504-7 layout of tables 497-8 of analyses 494-7 oral 507-9 principal components analysis (PCA) 129, 130, 443-4 assumptions 453-4 choice of association matrix 450-1 deriving components axis rotation 447-9 decomposing an association matrix 449-51 graphical representations biplots 456 scaling 454-6 interpreting the components 451 number of components to retain 452 analysis of residuals 452-3 eigenvalue equals one rule 452 scree diagram 452 tests of eigenvalue equality 452-3 other uses of components 456-7 principal components regression 457-8 relationship to MANOVA 456-7 robust 454 rotation of components 451-2 principal components regression 457-8 principal coordinates analysis (PCoA) 474-6

prior probability distributions 28 probability 7–9 probability density function 59, 60 probability distributions 9–10, 18 for statistics 12–13 for variables 9–12 process uncertainty 7 profile analysis, partly nested designs 319, 321–2 proportion of explained variance 91–2, 122–3, 137, 188, 190–1, 247, 249, 370, 405–6, 450

Q-mode analyses 412

R-estimators 16 R-mode analyses 412 r² 91-2, 122-3, 188, 370 random component, generalized linear models 359 random ANOVA effects, variance components 188-90 random effects ANOVA models 176-7 factorial designs 223, 236, 240 random sampling 14-15 random variables 7 randomization, experimental design 161 - 3randomization tests 45-6, 106, 143, 196, 250, 285, 352, 388, 482-4 randomized complete block (RCB) designs 262-4 adjusting univariate F tests 282-3 analysis of variance 272-3 and statistical software 298-9 comparing ANOVA models 274 interactions in unreplicated designs 277-80 linear effects model 269-71 multivariate tests 283-4 normality assumption 280-4 null hypotheses 273-4 power analysis 289-90 recommended strategy 284 robust 284-5 specific comparisons 285 sphericity assumption 281-2, 283 time as blocking factor 287 treatment by block interactions 274 - 7unbalanced 287-9 variances and covariances 280-4 (see also factorial randomized block designs; incomplete block designs)

ranging 68 rank transform (RT) method 47, 76, 196, 250 rank transformation 66–7 rank-based (non-parametric) regression 106 rank-based non-parametric tests 46-8, 195-6 RCB designs see randomized complete block designs reciprocal averaging 462 reciprocal transformations 65 reduced major axis (RMA) regression 101-2 redundancy analysis 466-7, 492 regression analysis see linear regression analysis regression slopes 85-6 comparing regression lines 352 heterogeneous within group 350-2 homogeneous within group 349-50 standardized 86 regression through the origin 98-9, 142 regression tree analysis 143-5, 146 repeated measures (RM) designs 265-6, 305-9 analysis of variance 272–3 and statistical software 298-9 assumptions 280-4 comparing ANOVA models 274 interaction in unreplicated designs 277 - 80linear models 268-72 null hypotheses 273-4 power analysis 289-90 robust 284-5 treatment by block interactions 274 - 7replication, experimental design 158-60 resampling-based adjusted P values 50 resampling methods for estimation 25 - 7residual plots factorial ANOVA 251 linear regression 96-8 multiple linear regression 126 randomized complete block ANOVA 277 - 8single factor ANOVA 194 residuals contingency tables 387-8 factorial ANOVA models 230

536 | INDEX

residuals (cont.) linear regression models 87, 95-6 logistic regression models 368-370 multiple regression models 125 nested ANOVA models 213-14 nonlinear models 152 partly nested ANOVA models 313 principal components analysis 453 randomized complete block and repeated measures ANOVA models 271-2, 277-8 single factor ANCOVA model 347 single factor ANOVA model 184, 194 two way contingency tables 387-8 response surfaces 153 restricted maximum likelihood estimation (REML) 190 ridge regression 129-30 RM designs see repeated measures (RM) designs robust analysis of covariance (ANCOVA) 352-3 robust correlation 76 robust factorial ANOVA 250 robust MANOVA 434 robust pairwise multiple comparisons 201 robust parametric tests 45 robust partly nested ANOVA 320 robust principal components analysis 454 robust randomized complete block ANOVA 284-5 robust regression 104-6, 143 robust single factor analysis of variance (ANOVA) 195 randomization tests 196 rank-based (non-parametric) tests 195 - 6tests with heterogeneous variances 195 running means 107 Ryan's test 200-1

sample coefficient of variation 17 sample range 16 sample size 14, 51–2, 157 sample space 52–3 sample standard deviation 17 sample variance 16, 20, 22 samples and populations 14–15 exploring 58–62 sampling designs 155–7 sampling distribution of the mean 18 scalable decision criteria 45 scaling and clustering for biological data 491-2 constrained 469-70 correspondence analysis 461-2 multidimensional 473-88, 492 principal components analysis 454-6 scanned images 509 scatterplot matrix (SPLOM) 61-2 scatterplots 61, 502-3 linear regression 96-7 multiple linear regression 125-6 Scheffe's test 201 Schwarz Bayesian information criterion (BIC) 139 scientific method 1-5 scree diagram 452 screening multivariate data sets 418-19 missing observations 419-20 multivariate outliers 419 sequential Bonferroni 50 significance levels 33 arbitrary 53 simple main effects test 252-3 simple random sampling 14, 155 single factor designs 173-6, 184-6 assumptions 191-4 independence 193-4 normality 192 variance homogeneity 193 comparing models 186-7 diagnostics 194-5 linear models 178-84 null hypothesis 186-7 power analysis 204-6 presentation of results 496 unequal sample sizes 187-8 single factor MANOVA linear combination 426, 430 null hypothesis 430-2 single variable goodness-of-fit tests 381 size of sample 14, 51-2, 157 skewed distributions 10-11, 62-3 transformations 65-6 small sample sizes, two way contingency tables 388 smoothing functions 107-9, 152-3 Spearman's rank correlation coefficient (r_s) 76 specific comparisons of means 196-7

planned comparisons or contrasts 197-8 specific contrasts versus unplanned pairwise comparisons 201 unplanned pairwise comparisons 199-201 sphericity partly nested designs 318-20 randomized complete block and repeated measures designs 281-3 splines 108 split-plot designs 301-5, 309 spread 16-17, 60 square root transformation 65 standard deviation 16-17 standard error of the mean 16, 18-19 standard errors for other statistics 21 - 3standard normal distribution 10 standard scores 18 standardizations 67-8 multivariate data 415-17 standardized partial regression slopes 123-4 standardized regression slopes 86, 123 standardized residuals 95 statistical analysis, role in scientific method 5 statistical hypothesis testing 32-54 alternatives to 53-4 associated probability and Type I error 34-5 classical 32-4 critique 51 arbitrary significance levels 53 dependence on sample size and stopping rules 51-2 null hypothesis always false 53 P values as measure of evidence 53 sample space - relevance of data not observed 52-3 Fisher's approach 33-4 hybrid approach 34 hypothesis tests for a single population 35-6 hypothesis tests for two populations 37-9 Neyman and Pearson's approach 33-4 one- and two-tailed tests 37 parametric tests and their assumptions 39-42

statistical population 14 statistical significance versus biological significance 44 statistical software and MANOVA 433 and partly nested designs 335-7 and randomized complete block designs 298-9 statistics 14 probability distributions 12-13 step-down analysis, MANOVA 432 stepwise variable selection 140 stopping rules 52 stratified sampling 156 structural equation modeling (SEM) 146-7, 150 Student-Neuman-Keuls (SNK) test 200 studentized residuals 95, 194 Student's t distribution 12 systematic component, generalized linear models 359 systematic sampling 156-7 t distribution 12-13, 19 t statistic 33, 35 t tests 35-6 assumptions 39-42 tables, layout of 497-8 test statistics 32-3 theoretic models 2-3 three way contingency tables 388-9 complete independence 393 conditional independence and odds ratios 389-93 log-linear models 395-400 marginal independence and odds ratios 393 time as blocking factor 287 tolerance values, multiple regression 128 transformations 96, 218, 415 and additivity 67, 280 and distributional assumptions 65-6 and linearity 67 angular transformations 66 arcsin transformation 66 Box-Cox family of transformations 66 factorial ANOVA models 249-50 fourth root transformations 65

linear regression models 98 logarithmic transformation 65 multiple linear regression models 127 power transformations 65-6 rank transformation 66-7 reciprocal transformations 65 square root transformation 65 transforming data 64-7 translation 67 treatment-contrast interactions 254 trends, tests for in single factor ANOVA 202-3 trimmed mean 15 truncated data 69-70 Tukey's HSD test 199-200 Tukey's test for (non)-additivity 278-80 two way contingency tables 381-2 log-linear models 394-5 null hypothesis 385-6, 394-5 odds and odds ratios 386–7 residuals 387-8 small sample sizes 388 table structure 382-5 two-tailed tests 37 Type I errors 34-5, 41-4 and multiple testing 48-9 graphical representation 43 Type II errors 34, 42-4, 164 graphical representation 43

unbalanced data 69 unbalanced designs ANCOVAs 353 factorial designs 241-7 nested designs 216-7 partly nested designs 322-3 randomized complete block designs 287-9 single factor (one way) designs 187-8 uncertainty 7 unequal sample sizes 69, 187-8 ANCOVAs 353 factorial designs 242-4 nested designs 216 partly nested designs 322-3 single factor (one way) designs 187-8 univariate ANOVAs, MANOVA 432 univariate F tests, adjusted 282-3, 319 unplanned comparisons of adjusted means, ANCOVA 353 unplanned pairwise comparisons of means 199-201 versus specific contrasts 201 unreplicated two factor experimental designs 263-8 interactions in 277-80 variability 16-17 variable selection procedure, multiple regression 139-40 variables 7 probability distributions 10-12 variance components 188-90, 216-18, 247, 249 variance inflation factor 128 variance-covariance matrix 402-3 variances 10, 16 confidence intervals 22-3, 189 homogeneity assumption factorial ANOVA models 249 linear models 63-4 linear regression models 93 nested ANOVA models 218 partly nested ANOVA models 318 randomized complete block ANOVA models 280-2 single factor ANOVA models 193 verbal models 2 Wald statistic 363-4. 367 Weibull distribution 11 weighted least squares 99-100, 142 Wilcox modification of Johnson-Neyman procedure 350 - 1Wilcoxon signed-rank test 47 Wilk's lambda 430-1

wink's fambua 450 T window width, smoothing functions 59–60 Winsorized mean 15

X random regression 100–4, 142–3

z distribution 10–13, 19 *z* scores 68 zero values 63, 69