

2	Assumptions and modelling philosophy	29
2.1	Assumptions	29
2.1.1	Assumption 1: objects on the line or point are detected with certainty	30
2.1.2	Assumption 2: objects are detected at their initial location	31
2.1.3	Assumption 3: measurements are exact	34
2.1.4	Other assumptions	36
2.2	Fundamental models	37
2.2.1	Line transects	37
2.2.2	Point transects	39
2.2.3	Summary	40
2.3	Philosophy and strategy	41
2.3.1	Model robustness	41
2.3.2	Shape criterion	42
2.3.3	Efficiency	42
2.3.4	Model fit	42
2.3.5	Test power	45
2.4	Robust models	45
2.5	Some analysis guidelines	48
2.5.1	Exploratory phase	48
2.5.2	Model selection	49
2.5.3	Final analysis and inference	50
3	Statistical theory	51
3.1	General formula	51
3.1.1	Standard distance sampling	51
3.1.2	Line transect sampling	52
3.1.3	Point transect sampling	54
3.1.4	Distance sampling with multipliers	57
3.2	The key function formulation for distance data	58
3.3	Maximum likelihood methods	61
3.3.1	Ungrouped data	61
3.3.2	Grouped data	62
3.3.3	Special cases	64
3.3.4	The half-normal detection function	65
3.3.5	Constrained maximum likelihood estimation	67
3.4	Choice of model	68
3.4.1	Criteria for robust estimation	68
3.4.2	Akaike's Information Criterion	69
3.4.3	The likelihood ratio test	70
3.4.4	Goodness of fit	71
3.5	Estimation for clustered populations	71
3.5.1	Truncation	72
3.5.2	Stratification by cluster size	72

3.5.3	Weighted average of cluster sizes	73
3.5.4	Regression estimators	73
3.5.5	Use of covariates	75
3.5.6	Replacing clusters by individual objects	75
3.6	Density, variance and interval estimation	76
3.6.1	Basic formulae	76
3.6.2	Replicate lines or points	78
3.6.3	The jackknife	80
3.6.4	The bootstrap	82
3.6.5	Estimating change in density	84
3.6.6	A finite population correction factor	86
3.7	Stratification and covariates	88
3.7.1	Stratification	89
3.7.2	Covariates	91
3.8	Efficient simulation of distance data	92
3.8.1	The general approach	92
3.8.2	The simulated line transect data of Chapter 4	95
3.8.3	The simulated size-biased point transect data of Chapter 5	97
3.8.4	Discussion	99
3.9	Exercises	99
4	Line transects	102
4.1	Introduction	102
4.2	Example data	103
4.3	Truncation	103
4.3.1	Right-truncation	103
4.3.2	Left-truncation	108
4.4	Estimating the variance in sample size	108
4.5	Analysis of grouped or ungrouped data	109
4.6	Model selection	110
4.6.1	The models	110
4.6.2	Akaike's Information Criterion	110
4.6.3	Likelihood ratio tests	112
4.6.4	Goodness of fit	113
4.7	Estimation of density and measures of precision	114
4.7.1	The standard analysis	114
4.7.2	Ignoring information from replicate lines	116
4.7.3	Bootstrap variances and confidence intervals	117
4.7.4	Satterthwaite degrees of freedom for confidence intervals	118
4.8	Estimation when the objects are in clusters	119
4.8.1	Observed cluster size independent of distance	119
4.8.2	Observed cluster size dependent on distance	122

4.9	Assumptions	130
4.9.1	Independence	130
4.9.2	Detection on the line	131
4.9.3	Movement prior to detection	131
4.9.4	Inaccuracy in distance measurements	132
4.10	Summary	133
4.11	Exercises	136
5	Point transects	146
5.1	Introduction	146
5.2	Example data	147
5.3	Truncation	151
5.3.1	Right-truncation	151
5.3.2	Left-truncation	153
5.4	Estimating the variance in sample size	154
5.5	Analysis of grouped or ungrouped data	155
5.6	Model selection	155
5.6.1	The models	155
5.6.2	Akaike's Information Criterion	156
5.6.3	Likelihood ratio tests	157
5.6.4	Goodness of fit	158
5.7	Estimation of density and measures of precision	159
5.7.1	The standard analysis	159
5.7.2	Bootstrap variances and confidence intervals	161
5.8	Estimation when the objects are in clusters	164
5.8.1	Standard method with additional truncation	167
5.8.2	Replacement of clusters by individuals	167
5.8.3	Stratification	170
5.8.4	Regression estimator	171
5.9	Assumptions	171
5.10	Summary	176
5.11	Exercises	178
6	Related methods	182
6.1	Introduction	182
6.2	Dung and nest surveys	183
6.2.1	Background	183
6.2.2	Field methods	184
6.2.3	Analysis	184
6.2.4	Assumptions	187
6.3	Line transect surveys for objects that are not continuously available for detection	189
6.3.1	Periods of detectability interspersed with periods of unavailability	189
6.3.2	Objects that give discrete cues	190

6.4	Cue counting	191
6.4.1	Introduction	191
6.4.2	Density estimation	192
6.4.3	Assumptions	194
6.4.4	Example	196
6.5	Distance sampling surveys for fast-moving objects	198
6.5.1	Line transect surveys	198
6.5.2	Point transect surveys	203
6.6	Other models	204
6.6.1	Binomial models	204
6.6.2	Estimators based on the empirical cdf	208
6.6.3	Estimators based on shape restrictions	210
6.6.4	Kernel estimators	211
6.6.5	Hazard-rate models	214
6.7	Distance sampling surveys when the observed area is incompletely covered	214
6.8	Trapping webs	216
6.8.1	Survey design and field methods	217
6.8.2	Assumptions	219
6.8.3	Estimation of density	219
6.8.4	Monte Carlo simulations	220
6.8.5	A simple example	221
6.8.6	Darkling beetle surveys	222
6.9	Point-to-object and nearest neighbour methods	223
6.10	Exercises	225
7	Study design and field methods	228
7.1	Introduction	228
7.2	Survey design	230
7.2.1	Transect layout	232
7.2.2	Sample size	240
7.3	Survey protocol and searching behaviour	249
7.3.1	Line transects	251
7.3.2	Point transects	253
7.4	Data measurement and recording	254
7.4.1	Distance measurement	254
7.4.2	Angle measurement	263
7.4.3	Distance measurement error	264
7.4.4	Cluster size	272
7.4.5	Line length measurement	273
7.4.6	Ancillary data	275
7.4.7	Data recording	275
7.5	Training observers	279
7.6	Aerial surveys	280
7.6.1	Aircraft and survey characteristics	281

7.6.2	Search and survey protocol	284
7.6.3	Distance measurement	286
7.7	Marine shipboard surveys	288
7.7.1	Vessel and survey characteristics	288
7.7.2	Search and survey protocol	289
7.7.3	Distance measurement	290
7.8	Land-based surveys	291
7.8.1	Surveys of small objects	291
7.8.2	Stratification by habitat	293
7.8.3	Permanent transects and repeat transects	293
7.8.4	Cut transects	294
7.8.5	Roads, tracks and paths as transects	295
7.8.6	Spotlight and thermal imager surveys	296
7.8.7	Objects detected away from the line	298
7.8.8	Bird surveys	298
7.8.9	Surveys in riparian habitats	300
7.9	Special circumstances	301
7.9.1	Multi-species surveys	301
7.9.2	Surveys of animals that occur at high densities	302
7.9.3	One-sided transects	304
7.9.4	Uneven terrain and contour transects	306
7.9.5	Uncertain detection on the trackline	307
7.10	Field comparisons between line transects, point transects and mapping censuses	310
7.10.1	Breeding birds in Californian coastal scrub	310
7.10.2	Breeding birds in Sierran subalpine forest	311
7.10.3	Bobolink surveys in New York state	312
7.10.4	Breeding birds in Californian oak-pine woodlands	313
7.10.5	Breeding birds along the Colorado River	314
7.10.6	Birds of Miller Sands Island, Oregon	315
7.10.7	Concluding remarks	315
7.11	Exercises	317
8	Illustrative examples	324
8.1	Introduction	324
8.2	Lake Huron brick data	324
8.3	Wooden stake data	326
8.4	Studies of nest density	332
8.4.1	Spatial distribution of duck nests	335
8.4.2	Estimation of density	338
8.4.3	Nest detection in differing habitat types	346
8.4.4	Models for the detection function $g(x)$	348
8.4.5	Estimating trend in nest numbers	350
8.5	Fin whale abundance in the North Atlantic	351

CONTENTS

xv

8.6	House wren densities in South Platte River bottomland	361
8.7	Songbird point transect surveys in Arapaho NWR	366
8.8	Assessing the effects of habitat on density	375
Bibliography		381
Common and scientific names of plants and animals		421
Glossary of notation and abbreviations		424
Index		427