

Contents

1 Introduction	1
1.1 The design-based paradigm	2
1.2 Text content and orientation	4
1.3 What distinguishes this text?	5
1.4 Recommendations for instructors	6
1.5 Sampling theory: A brief history	7
2 Basic concepts	11
2.1 Terminology	12
2.2 Components of a sampling strategy	13
2.3 Selection methods	14
2.4 Properties of estimators	15
2.5 Sampling distribution of an estimator	18
2.6 Judgment sampling versus random sampling	19
3 Equal probability sampling	23
3.1 Without replacement sampling	23
3.1.1 Estimation of the population mean, proportion, and total	25
3.1.2 Sampling variance	27
3.1.3 Estimation of sampling variance	30
3.1.4 Bernoulli sampling	31
3.2 With replacement sampling	32
3.2.1 Estimation of the population mean, proportion, and total	34
3.2.2 Sampling variance and variance estimation	35
3.2.3 Rao–Blackwell theorem	35
3.3 Relative performance of alternative sampling strategies	36
3.3.1 Measures of relative performance	36
3.3.2 An example: SRS/mean-per-unit estimation versus SWR	37
3.4 Sample size to achieve desired level of precision	38
3.4.1 Approximate normality of sampling distributions	38
3.4.2 Confidence interval construction	40
3.4.3 Sample size determination	40
3.5 Nonresponse and oversampling	42

3.6	Sampling in R	44
3.6.1	SRS and SWR	44
3.6.2	Sample spaces	44
3.7	Chapter comments	45
	Problems	45
4	Systematic sampling	48
4.1	Linear systematic sampling	50
4.1.1	N/k is integer-valued	50
4.1.2	N/k is not integer-valued	52
4.2	Selection methods that guarantee fixed n	53
4.2.1	Circular systematic sampling	53
4.2.2	Fractional interval random start	54
4.3	Estimation of sampling variance	57
4.3.1	Biased estimation	57
4.3.2	Unbiased estimation	58
4.4	Unpredictable trend in sampling variance with n	62
4.5	Warning: Pathological settings	62
4.6	Nonresponse and oversampling	63
4.7	Chapter comments	64
	Problems	65
5	Stratified sampling	68
5.1	Estimation of the population mean	69
5.1.1	Expected value	69
5.1.2	Sampling variance	70
5.1.3	Numerical examples	70
5.2	Estimation of the population proportion	72
5.3	Estimation of the population total	72
5.4	Estimation of sampling variance	73
5.5	Allocation of the sample across strata	74
5.5.1	Optimal allocation: Graphical analysis	75
5.5.2	Optimal allocation: Analytical analysis	75
5.5.3	Comments on optimal allocation	78
5.6	Sample size determination	79
5.7	Relative efficiency	80
5.7.1	Proportional allocation	80
5.7.2	Estimation of finite population variance	81
5.8	Effective degrees of freedom	83
5.9	Post-stratification	84
5.9.1	Unconditional sampling variance	85
5.9.2	Conditional sampling variance	86
5.10	Chapter comments	87
	Problems	88

6 Single-stage cluster sampling: Clusters of equal size	92
6.1 Estimation of the population mean	93
6.2 Sampling variance	94
6.2.1 ANOVA/mean squares approach	95
6.2.2 Intraclass correlation approach	96
6.3 Estimation of the population total and proportion	97
6.4 Estimation of sampling variance	98
6.5 Estimation of finite population variance	99
6.6 Sample size determination	100
6.7 Relative efficiency	100
6.8 Chapter comments	101
Problems	102
7 Ratio and regression estimation	104
7.1 Estimation of the mean and total	105
7.1.1 Graphical representation	106
7.1.2 Sample space illustration	107
7.1.3 Bias	109
7.1.4 Sampling variance	110
7.1.5 Estimation of sampling variance	112
7.1.6 Sample size determination	112
7.1.7 Relative efficiency	113
7.2 Ratio estimation of a proportion	115
7.3 Ratio estimation with stratified sampling	117
7.3.1 Combined estimator	117
7.3.2 Separate estimator	117
7.3.3 Choosing between combined and separate estimators	118
7.4 A model-based perspective	118
7.4.1 Estimation of model parameters	119
7.4.2 Prediction of population parameters	124
7.4.3 Prediction error	126
7.4.4 Prediction variance estimators	128
7.5 Monte Carlo performance evaluation	129
7.6 Mark-recapture estimation	132
7.7 Chapter comments	133
Problems	135
8 Unequal probability sampling	140
8.1 Unbiased ratio estimator	141
8.2 Sampling with replacement	143
8.2.1 Hansen–Hurwitz estimator	143
8.2.2 Unbiasedness	144
8.2.3 Sampling variance and variance estimation	144
8.3 Sampling without replacement	145

8.3.1	Horvitz–Thompson estimator	146
8.3.2	Unbiasedness	147
8.3.3	Sampling variance and variance estimation	148
8.3.4	Alternative selection methods	150
8.3.5	Strategy performance comparisons	152
8.3.6	Survey cost comparisons	155
8.4	Sampling distribution	157
8.5	Systematic sampling	159
8.6	Generality of Horvitz–Thompson estimation	161
8.7	Generalized Horvitz–Thompson estimation	162
8.7.1	Variance, covariance, and correlation estimators	163
8.7.2	Mean-per-unit, ratio, and regression estimators	163
8.7.3	Performance of generalized Horvitz–Thompson estimators	163
8.8	Poisson sampling	164
8.9	Nonresponse and oversampling	165
8.9.1	Hansen–Hurwitz estimator	165
8.9.2	Horvitz–Thompson estimator	166
8.10	Chapter comments	167
	Problems	168
9	Multi-stage sampling	173
9.1	Two-stage sampling: Clusters of equal size	174
9.1.1	Estimation of the population mean	175
9.1.2	Expectation	176
9.1.3	Sampling variance and its estimation	179
9.1.4	Optimal allocation	181
9.1.5	Net relative efficiency	184
9.2	Two-stage sampling: Clusters of unequal size	185
9.2.1	Single-stage cluster sampling	185
9.2.2	Two-stage estimation of the population mean and total	187
9.2.3	Sampling variance and its estimation	187
9.2.4	Optimal allocation	194
9.3	Chapter comments	195
9.3.1	Generality of the multi-stage framework	195
9.3.2	Taking advantage of ecological understanding	196
9.3.3	Implications for large-scale natural resource surveys	196
	Problems	197
10	Multi-phase sampling	200
10.1	Two-phase estimation of the population mean and total	201
10.1.1	Estimators	202
10.1.2	Sampling variance and its estimation	202
10.1.3	Sample space illustration	203
10.1.4	Optimal allocation	205
10.1.5	Net relative efficiency	207

10.2	Two-phase ratio estimation of a proportion	209
10.3	Two-phase sampling with stratification	212
10.3.1	Estimation of the population mean and total	212
10.3.2	Sampling variance and its estimation	212
10.3.3	Optimal allocation	213
10.3.4	Net relative efficiency	215
10.4	Chapter comments	215
	Problems	216
11	Adaptive sampling	219
11.1	Adaptive cluster sampling	220
11.1.1	Basic scheme	220
11.1.2	Definitions	221
11.1.3	Inclusion probabilities and expected sample size	222
11.1.4	Estimators and relative efficiency	224
11.2	Other adaptive sampling designs	231
11.2.1	Single-stage strip and systematic designs	231
11.2.2	Two-stage complete allocation cluster sampling	232
11.3	Chapter comments	236
	Problems	238
12	Spatially balanced sampling	240
12.1	Introduction	240
12.2	Finite populations	244
12.2.1	Generalized random tessellation stratified sampling	244
12.2.2	Balanced acceptance sampling	251
12.2.3	Estimation	260
12.3	Infinite populations	263
12.3.1	Generalized random tessellation stratified sampling	263
12.3.2	Balanced acceptance sampling	264
12.3.3	Estimation	265
12.4	Chapter comments	266
13	Sampling through time	269
13.1	Sampling on two occasions	270
13.1.1	Design 1: Full retention of units across occasions	271
13.1.2	Design 2: Independent SRS on each occasion	272
13.1.3	Comparison of full retention and independent SRS designs	272
13.1.4	Design 3: Partial retention/partial replacement	273
13.2	Monitoring design	275
13.2.1	Membership design	276
13.2.2	Revisit design	277
13.3	Estimation of status and trend	282
13.3.1	Design-based estimation	283
13.3.2	Estimators for some specific designs	284

13.4	Sample size determination	286
13.5	Dual frame sampling	288
13.6	Chapter comments	290
A	Mathematical foundations	295
A.1	Counting techniques	296
A.1.1	Permutations	296
A.1.2	k-Permutations	296
A.1.3	Combinations	298
A.1.4	Partitions	298
A.2	Basic principles of probability theory	299
A.2.1	Random experiment	299
A.2.2	Sample space	300
A.2.3	Outcome probability	300
A.2.4	Event	301
A.2.5	Event relations	301
A.2.6	Union and intersection	302
A.2.7	Conditional probability	302
A.2.8	Other probability relations	302
A.3	Discrete random variables	303
A.3.1	Definition	303
A.3.2	Probability distributions	303
A.3.3	Probability relations	305
A.3.4	Expectation	305
A.3.5	Variance and coefficient of variation	307
A.3.6	Covariance and correlation	309
A.3.7	Total expectation and variance	310
A.3.8	Indicator variables	311
A.4	Key discrete probability distributions	312
A.4.1	Uniform	312
A.4.2	Bernoulli	313
A.4.3	Multinoulli	313
A.4.4	Binomial	314
A.4.5	Multinomial	315
A.4.6	Hypergeometric	316
A.4.7	Multivariate hypergeometric	317
A.5	Population variables	317
A.5.1	Definition	317
A.5.2	Population parameters	318
A.6	Probability sampling	319
A.6.1	Sampling experiment	319
A.6.2	Sampling designs	320
A.6.3	Inclusion probabilities	320
A.6.4	Inclusion indicator variables	320

A.7	Estimators	321
A.7.1	Definition	321
A.7.2	Sampling distribution	322
A.7.3	Statistical properties	323
A.7.4	Confidence intervals	324
A.8	Delta method	325
A.9	Lagrange multipliers	327
References		329
Index		337