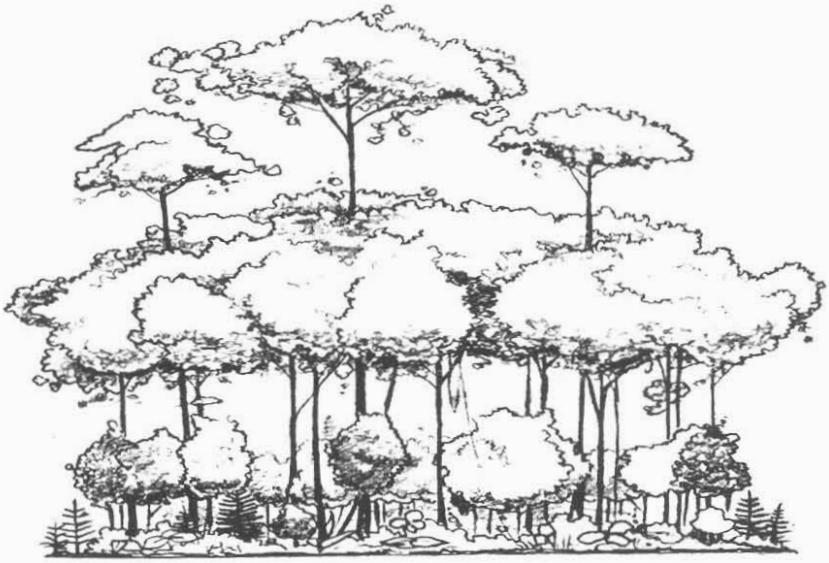
MANAGING FOREST ECOSYSTEMS

Forest Inventory

Methodology and Applications

Edited by
Annika Kangas and Matti Maltamo



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FOREST INVENTORY

Managing Forest Ecosystems

Volume 10

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Aims & Scope:

Well-managed forests and woodlands are a renewable resource, producing essential raw material with minimum waste and energy use. Rich in habitat and species diversity, forests may contribute to increased ecosystem stability. They can absorb the effects of unwanted deposition and other disturbances and protect neighbouring ecosystems by maintaining stable nutrient and energy cycles and by preventing soil degradation and erosion. They provide much-needed recreation and their continued existence contributes to stabilizing rural communities.

Forests are managed for timber production and species, habitat and process conservation. A subtle shift from *multiple-use management* to *ecosystems management* is being observed and the new ecological perspective of *multi-functional forest management* is based on the principles of ecosystem diversity, stability and elasticity, and the dynamic equilibrium of primary and secondary production.

Making full use of new technology is one of the challenges facing forest management today. Resource information must be obtained with a limited budget. This requires better timing of resource assessment activities and improved use of multiple data sources. Sound ecosystems management, like any other management activity, relies on effective forecasting and operational control.

The aim of the book series ***Managing Forest Ecosystems*** is to present state-of-the-art research results relating to the practice of forest management. Contributions are solicited from prominent authors. Each reference book, monograph or proceedings volume will be focused to deal with a specific context. Typical issues of the series are: resource assessment techniques, evaluating sustainability for even-aged and uneven-aged forests, multi-objective management, predicting forest development, optimizing forest management, biodiversity management and monitoring, risk assessment and economic analysis.

The titles published in this series are listed at the end of this volume.

Forest Inventory

Methodology and Applications

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TABLE OF CONTENTS

PREFACE xiii
ACKNOWLEDGEMENTS xv
LIST OF CONTRIBUTING AUTHORS xvii

PART I Theory

1. INTRODUCTION 3
Annika Kangas, Jeffrey H. Gove and Charles T. Scott
1.1 GENERAL 3
1.2 HISTORICAL BACKGROUND OF SAMPLING THEORY 4
1.3 HISTORY OF FOREST INVENTORIES 5
REFERENCES 8

2. DESIGN-BASED SAMPLING AND INFERENCE 13
Annika Kangas
2.1 BASIS FOR PROBABILITY SAMPLING 13
2.2 SIMPLE RANDOM SAMPLING 15
2.3 DETERMINING THE SAMPLE SIZE 17
2.4 SYSTEMATIC SAMPLING 18
2.5 STRATIFIED SAMPLING 24
2.6 CLUSTER SAMPLING 28
2.7 RATIO AND REGRESSION ESTIMATORS 29
2.8 SAMPLING WITH PROBABILITY PROPORTIONAL TO SIZE 32
2.9 NON-LINEAR ESTIMATORS 32
2.10 RESAMPLING 34
2.11 SELECTING THE SAMPLING METHOD 35
REFERENCES 37

3. MODEL-BASED INFERENCE 39
Annika Kangas
3.1 FOUNDATIONS OF MODEL-BASED INFERENCE 39
3.2 MODELS 41
3.3 APPLICATIONS OF MODEL-BASED METHODS TO FOREST INVENTORY 46
3.4 MODEL-BASED VERSUS DESIGN-BASED INFERENCE 48
REFERENCES 50

4. MENSURATIONAL ASPECTS 53
Annika Kangas
4.1 SAMPLE PLOTS 53
4.1.1 Plot size 53
4.1.2 Plot shape 54
4.2 POINT SAMPLING 55

4.3 COMPARISON OF FIXED-SIZED PLOTS AND POINTS 57
4.4 PLOTS LOCATED ON AN EDGE OR SLOPE 58
4.4.1 Edge corrections 58
4.4.2 Slope corrections 61
REFERENCES 62

5. CHANGE MONITORING WITH PERMANENT SAMPLE PLOTS 65
Simo Poso
5.1 CONCEPTS AND NOTATIONS 65
5.2 CHOICE OF SAMPLE PLOT TYPE AND TREE MEASUREMENT 69
5.3 ESTIMATING COMPONENTS OF GROWTH AT THE PLOT LEVEL 70
5.4 MONITORING VOLUME AND VOLUME INCREMENT OVER TWO OR MORE MEASURING PERIODS AT THE PLOT LEVEL 73
5.5 ESTIMATING POPULATION PARAMETERS 79
5.6 CONCLUDING REMARKS 82
REFERENCES 83

6. GENERALIZING SAMPLE TREE INFORMATION 85
Juha Lappi, Lauri Mehtätalo and Kari T. Korhonen
6.1 ESTIMATION OF TALLY TREE REGRESSION 85
6.2 GENERALIZING SAMPLE TREE INFORMATION IN A SMALL SUBPOPULATION 91
6.2.1 Mixed estimation 92
6.2.2 Applying mixed models 92
6.3 A CLOSER LOOK AT THE THREE-LEVEL MODEL STRUCTURE 100
REFERENCES 105

7. USE OF ADDITIONAL INFORMATION 107
Juha Lappi and Annika Kangas
7.1 CALIBRATION ESTIMATION 107
7.2 SMALL AREA ESTIMATES 110
REFERENCES 116

8. SAMPLING RARE POPULATIONS 119
Annika Kangas
8.1 METHODS FOR SAMPLING RARE POPULATIONS 119
8.1.1 Principles 119
8.1.2 Strip sampling 120
8.1.3 Line intersect sampling 121
8.1.4 Adaptive cluster sampling 125
8.1.5 Transect and point relascope sampling 128
8.1.6 Guided transect sampling 130

8.2 WILDLIFE POPULATIONS 133
8.2.1 Line transect sampling 133
8.2.2 Capture-recapture methods 135
8.2.3 The wildlife triangle scheme 136

REFERENCES 137

9. INVENTORIES OF VEGETATION, WILD BERRIES AND MUSHROOMS 141
Matti Maltamo
9.1 BASIC PRINCIPLES 141
9.2 VEGETATION INVENTORIES 141
9.2.1 Approaches to the description of vegetation 141
9.2.2 Recording of abundance 143
9.2.3 Sampling methods for vegetation analysis 144
9.3 EXAMPLES OF VEGETATION SURVEYS 146
9.4 INVENTORIES OF MUSHROOMS AND WILD BERRIES 148
REFERENCES 150

10. ASSESSMENT OF UNCERTAINTY IN SPATIALLY SYSTEMATIC SAMPLING 155
Juha Heikkinen
10.1 INTRODUCTION 155
10.2 NOTATION, DEFINITIONS AND ASSUMPTIONS 157
10.3 VARIANCE ESTIMATORS BASED ON LOCAL DIFFERENCES 158
10.3.1 Restrictions of SRS-estimator 158
10.3.2 Development of estimators based on local differences 160
10.4 VARIANCE ESTIMATION IN THE NATIONAL FOREST INVENTORY IN FINLAND 162
10.5 MODEL-BASED APPROACHES 164
10.5.1 Modelling spatial variation 165
10.5.2 Model-based variance and its estimation 167
10.5.3 Descriptive versus analytic inference 171
10.5.4 Kriging in inventories 172
10.6 OTHER SOURCES OF UNCERTAINTY 174
REFERENCES 174

PART II Applications

11. THE FINNISH NATIONAL FOREST INVENTORY 179
Erkki Tomppo
11.1 INTRODUCTION 179
11.2 FIELD SAMPLING SYSTEM USED IN NFI9 181
11.3 ESTIMATION BASED ON FIELD DATA 184
11.3.1 Area estimation 185
11.3.2 Volume estimation 185

11.3.2.1 Predicting sample tree volumes and volumes by timber assortment classes 186
11.3.2.2 Predicting volumes for tally trees 186
11.3.3.3 Computing volumes for computation units 187
11.4 INCREMENT ESTIMATION 188
11.5 CONCLUSIONS 192
REFERENCES 193

12. THE FINNISH MULTI-SOURCE NATIONAL FOREST INVENTORY – SMALL AREA ESTIMATION AND MAP PRODUCTION 195
Erkki Tomppo
12.1 INTRODUCTION 195
12.1.1 Background 195
12.1.2 Progress in the Finnish multi-source inventory 198
12.2 INPUT DATA SETS FOR THE BASIC AND IMPROVED k-NN METHODS 199
12.2.1 Processing of field data for multi-source calculations 199
12.2.2 Satellite images 200
12.2.3 Digital map data 201
12.2.4 Large-area forest resource data 201
12.3 BASIC k-NN ESTIMATION 202
12.4 THE IMPROVED k-NN, (ik-NN) METHOD 208
12.4.1 Simplified sketch of the genetic algorithm 211
12.4.2 Application of the algorithm 213
12.4.3 Reductions of the bias and standard error of the estimates at the pixel level and regional level 214
12.5 CONCLUSIONS 219
REFERENCES 221

13. CORRECTING MAP ERRORS IN FOREST INVENTORY ESTIMATES FOR SMALL AREAS 225
Matti Katila
13.1 INTRODUCTION 225
13.2 LAND USE CLASS AREAS 226
13.3 CALIBRATED PLOT WEIGHTS 228
REFERENCES 233

14. MULTIPHASE SAMPLING 235
Sakari Tuominen, Markus Holopainen and Simo Poso
14.1 INTRODUCTION 235
14.2 DOUBLE SAMPLING FOR STRATIFICATION WHEN ESTIMATING POPULATION PARAMETERS 236
14.3 DOUBLE SAMPLING FOR REGRESSION 242
14.4 FOREST INVENTORY APPLICATIONS OF TWO-PHASE SAMPLING 243
14.4.1 The grouping method – two-phase sampling for stratification with one second-phase unit per stratum 243

14.4.2 Stratification with mean vector estimation 245
14.4.3 K nearest neighbour method with mean vector estimation 246
14.5 MULTI-PHASE SAMPLING WITH MORE THAN TWO PHASES 248
14.6 ESTIMATION TESTING 248
14.7 CONCLUDING REMARKS 250
REFERENCES 251

15. SEGMENTATION 253
Anssi Pekkarinen and Markus Holopainen
15.1 INTRODUCTION 253
15.2 IMAGE SEGMENTATION 254
15.2.1 General 254
15.2.2 Image segmentation techniques 254
15.2.3 Segmentation software 256
15.3 SEGMENTATION IN FOREST INVENTORIES 257
15.4 SEGMENTATION EXAMPLES 258
15.4.1 General 258
15.4.2 Example material 259
15.4.3 Example 1: Pixel-based segmentation 260
15.4.4 Example 2: Edge detection 262
15.4.5 Example 3: Region segmentation 265
REFERENCES 267

16. INVENTORY BY COMPARTMENTS 271
Jyrki Koivuniemi and Kari T. Korhonen
16.1 BASIC CONCEPTS AND BACKGROUND 271
16.2 HISTORY OF THE INVENTORY METHOD IN FINLAND 272
16.3 INVENTORY BY COMPARTMENTS TODAY 272
16.3.1 The inventory method 272
16.3.2 Estimation methods 274
16.4 ACCURACY IN THE INVENTORY BY COMPARTMENTS METHOD AND SOURCES OF ERROR 275
REFERENCES 277

17. ASSESSING THE WORLD'S FORESTS 279
Annika Kangas
17.1 GLOBAL ISSUES 279
17.1.1 Issues of interest 279
17.1.2 Forest area 281
17.1.3 Wood volume and woody biomass 281
17.1.4 Biodiversity and conservation 282
17.2 METHODOLOGY 284
17.2.1 Global forest resources assessment 284

17.2.2 Temperate and boreal forest assessment 285
17.2.3 Pan-tropical remote sensing survey 286
17.2.4 Global mapping 288
17.2.5 Forest information database 290
REFERENCES 290

PART III Cases

18. EUROPE 295
Timo Tokola
18.1 SWEDEN 295
18.1.1 Swedish National Forest Inventory 295
18.1.2 Inventory for forest management planning 298
18.2 GERMANY 299
18.2.1 National Forest Inventory: Natural forests 300
18.2.2 Regional inventories 303
18.2.3 Forest management planning: compartment level inventory 303
18.3 OTHER EUROPEAN AREAS 304
REFERENCES 307

19. ASIA 309
Timo Tokola
19.1 INDIA 309
19.1.1 Forest cover mapping 310
19.1.2 Forest inventory 311
19.1.3 Trees outside the forest (TOF) and the household survey 314
19.1.4 Forest management planning 315
19.2 INDONESIA 316
19.2.1 The National Forest Inventory 316
19.2.2 Concession renewal mapping 318
19.2.3 Forest management planning: compartment-level inventories of natural forests 319
19.2.4 Forest management planning: compartment-level inventories of plantation forests 320
19.3 CHINA 321
19.3.1 National Forest Inventory: natural forests 322
19.3.2 Forest management planning: compartment-level inventories 322
19.4 OTHER ASIAN AREAS 323
REFERENCES 324

20. NORTH AMERICA 325
Timo Tokola
20.1 CANADA 325
20.1.1 Provincial-level management inventories 326
20.1.2 National forest inventories, national aggregation 327
20.1.3 Industrial forest management inventories 329

20.2 THE UNITED STATES OF AMERICA 332
20.2.1 The National Forest Inventory 333
20.2.2 Industrial forest management planning: stand-level inventory 337
20.2.3 Cruising, scaling and volume estimation 337
20.3 MEXICO 338
REFERENCES 339

PART IV Future

21. MODERN DATA ACQUISITION FOR FOREST INVENTORIES
Markus Holopainen and Jouni Kalliovirta 343
21.1 INTRODUCTION 343
21.2 REMOTE SENSING 343
21.2.1 Digital aerial photos 343
21.2.2 Spectrometer imagery 344
21.2.3 High-resolution satellite imagery 344
21.2.4 Microwave radars 344
21.2.5 Profile imaging 345
21.2.6 Laser scanning 345
21.3 USE OF MODERN REMOTE SENSING IN FOREST INVENTORIES 346
21.3.1 Accuracy of remote sensing in forest inventories 346
21.3.2 Stand-, plot- and tree-level measurements on digital aerial photographs 348
21.3.3 Stand-, plot- and tree-level measurements using laser scanning 351
21.3.4 Integration of laser scanning and aerial imagery 352
21.4 IMPROVING THE QUALITY OF GROUND-TRUTH DATA IN REMOTE SENSING ANALYSIS 352
21.4.1 Development of field measuring devices 352
21.4.1.1 Terrestrial lasers 353
21.4.1.2 Laser-relascope 354
21.4.1.3 Digital cameras 356
21.4.2 Field data acquisition by logging machines 357
REFERENCES 357

PREFACE

This book has been developed as a forest inventory textbook for students and could also serve as a handbook for practical foresters. We have set out to keep the mathematics in the book at a fairly non-technical level, and therefore, although we deal with many issues that include highly sophisticated methodology, we try to present first and foremost the ideas behind them. For foresters who need more details, references are given to more advanced scientific papers and books in the fields of statistics and biometrics.

Forest inventory books deal mostly with sampling and measurement issues, as found here in section I, but since forest inventories in many countries involve much more than this, we have also included material on forestry applications. Most applications nowadays involve remote sensing technology of some sort, so that section II deals mostly with the use of remote sensing material for this purpose. Section III deals with national inventories carried out in different parts of world, and section IV is an attempt to outline some future possibilities of forest inventory methodologies.

The editors,

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PART I
THEORY

CHAPTER 1

INTRODUCTION

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1.1 GENERAL

All decision-making requires information. In forestry, this information is acquired by means of forest inventories, systems for measuring the extent, quantity and condition of forests (Penman et al. 2003). More specifically, the purpose of forest inventories is to estimate means and totals for measures of forest characteristics over a defined area. Such characteristics include the volume of the growing stock, the area of a certain type of forest and nowadays also measures concerned with forest biodiversity, e.g. the volume of dead wood or vegetation (Chapters 8 and 9). This book presents methods and applications for carrying out a forest inventory in different situations.

A forest inventory could in principle be based on a complete census, i.e. on measuring every tree in a given area, but this is usually impossible in forestry because of the large areas involved. Therefore the acquisition of information is typically based on sampling, i.e. only a proportion of the population, a sample, is inspected and inferences regarding the whole population are based on this sample.

There are two main schools of inference in sampling theory, design-based and model-based. In design-based inference, the randomness in the sampling is solely due to the random selection of sampling units (Chapter 2). The population values y_i are regarded as fixed, but unknown. Inference is based on the variation between all possible samples of size n that can be drawn from the population with a given sampling design. The confidence intervals obtained are to be interpreted on the assumption of a hypothetical repetition of samples.

This is not the case in model-based inference (Chapter 3), where the randomness is solely due to the model used for describing the population. In this case, the sampling method does not necessarily have to be random, but the possible correlation between sampling units needs to be accounted for.

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Forest inventory is more than sampling, however. Measuring trees and sample plots (Chapter 4) includes many methodological problems that are typical only to this sphere. Forest inventories cover different spatial scales from the stand level to the woodlot level, regional and country level and finally global level. It is evident that these varying scales also require different methodologies. The purposes of inventories may also vary. Stand-level inventories (Chapter 16) can be carried out in order to estimate the number of saplings after regeneration, woodlot-level inventories in order to facilitate harvesting or silvicultural decisions, and regional or country-level inventories in order to enhance policy decisions (Chapters 18-20). Global inventories (Chapter 17) may also serve certain purposes in global-level politics, such as international agreements over actions concerning biodiversity or global warming.

Forest inventories may also be means of estimating the current growing stock, but most often they are carried out at several points of time in order to analyse temporal changes (Chapter 5).

1.2 HISTORICAL BACKGROUND OF SAMPLING THEORY

The use of representative samples was recommended by A. N. Kiaer, a Norwegian statistician, at the end of the 19th century (Bellhouse 1988). Reactions to his recommendation were mainly negative at first, but by 1925 the idea was generally accepted. The idea of samples had been introduced even earlier, but it was Kiaer's campaign that provided the breakthrough for its acceptance (Bellhouse 1988).

In those days the samples were, for most part, purposely selected. The idea of randomization was introduced into survey sampling by A. L. Bowley in 1912 (Bellhouse 1988), but the use of purposive selection remained acceptable for the next decade. Bowley also studied the precision of the estimates obtained, and found purposive sampling to be more efficient than random sampling.

The paper of Neyman (1934) gave the first precise statistical framework for sampling theory. He presented confidence intervals for sample estimates, based on their distribution among all the possible samples of a given size from the given population, so that the estimates for the confidence intervals would apply irrespective of the properties of the original population (except when the sample was very small or the population extremely skewed).

Neyman also provided the reasons why randomization gave a more reasonable solution than purposive selection and outlined the assumptions under which purposive selection would work well, namely when there is a linear relationship between the variable of interest and the available covariates (Bellhouse 1988). Since Neyman's paper random sampling has superseded purposive sampling. Neyman also presented the principles of stratified sampling (1934), although the same ideas had already been put forward by Tschuprow (1923, see Schreuder et al. 1993).

During the next two decades classical sampling theory, or design-based theory as it is called, achieved mathematical and practical acceptance, essentially in the form in which it is used today. The most important developments in design-based theory during those decades were related to sampling with unequal

probabilities (Hansen and Hurwitz 1943), a method by which the precision of the results could, under some conditions, be radically improved. Horwitz and Thompson (1952) provided an unbiased estimator for unequal probability sampling.

The first challenge to the design-based approach was raised by V. P. Godambe in 1955. He showed that no minimum variance unbiased estimator exists among all possible linear unbiased estimators, even for simple random sampling (Rao and Bellhouse 1990). This means that certain estimators for population parameters (such as the sample mean) would not have the minimum variance in all populations. In order to find the best estimator, some assumptions therefore had to be made concerning the population. This aroused interest in an alternative approach to sampling theory, the model-based approach (also called the model-dependent or prediction approach). The foundations of this approach were introduced by Godambe (1955) and later established by Cassel et al. (1977).

1.3 HISTORY OF FOREST INVENTORIES

The main method used in inventories in the 19th century was complete enumeration, but it was soon noted that there was a possibility to reduce costs by using representative samples (Loetsch et al. 1973). Sampling-based methods were used in forestry a century before the mathematical foundations of sampling techniques were described (Doig 1976, Seppälä 1985, Honer and Hegyi 1990, Gregoire 1992, van Hooser et al. 1992, Schreuder et al. 1993, Frayer and Furnival 1999).

In the early days visual estimation was often used, as it was cheap and fast. In North America, for instance, these inventory surveys were carried out at the beginning of the 20th century by "timber lookers", whose years of field experience allowed them to develop the ability to assess timber volumes by eye without the benefit of any measurements. One early common practice was to estimate the volume on an "average tree" within a plot of fixed size and, by knowing the count of stems on the plot, thereby estimate volume on an "average acre", finally expanding to the yield on the tract of land (Graves 1906, p.192). According to Loetch et al. (1973), visual estimation was used until the 1940's in Germany, where learning this method was part of a good training program for a forester in those days. In the Nordic countries, especially in Finland, these visual estimates are still used for acquiring data for management planning at the stand level. In early inventories visual estimates could also be combined with statistical estimates in order to reduce bias (Cajanus 1913, Ilvessalo 1923).

Statistical knowledge was gradually introduced into the forestry literature between 1900 and 1920, primarily in Scandinavia (Loetsch et al. 1973), where the first small-scale forest inventories using systematic strip sampling had been carried out in Sweden in the 1830's by Israel af Ström. An auxiliary purpose in conducting an inventory was that of developing a map showing the distribution of timber, forest types, access and topographic detail. The method of cruising with continuous strips of fixed width covering a known percentage of the land area was most popular into the 1930s because it served both purposes, inventory and mapping.

The most important scientific work in this field in Finland was the inventory carried out in Sahalahti and Kuhmalahti by Werner Cajanus in 1912 (Seppälä 1985). Yrjö Ilvessalo carried out the first four National Forest Inventories between 1921 and 1963 (1927, 1942, 1956, 1962). National inventories in the other Nordic countries started at almost the same time. Since these first inventories were systematic, estimators for the variance in systematic sampling have been intensively developed in these countries (e.g. Lindeberg 1924, 1926, Langsaeter 1926, 1932, Östling 1932, Chapter 10).

However, the systematic use of strips was not the most efficient method. Thus, there began a slow shift from the use of strips to the use of the line-plot system: a systematic sampling design in which relatively small square or, more commonly, circular plots, were taken at set intervals (Robertson 1927). The line-plot method had the advantage of surveying a much smaller percentage of the area for a given accuracy, while still providing a method for mapping.

The next few decades brought a flurry of activity on the application of statistical methods to forest inventory. In the United States, Schumacher and Bull (1932) began the formalization of statistical sampling methods applied to forest inventories, with specific regard to the estimation of sampling errors. Mudgett and Gevorkiantz (1934) also looked at methods for assessing the reliability of area estimates using binomial, Poisson, and Lexian models according to differing assumptions about the random or stratified nature of the populations being sampled. Girard and Gevorkiantz (1939) devoted a large part of their monograph to the calculation of sampling errors, and interestingly, it was evidently Schumacher and Chapman (1942) who published the first known book on sampling in any field.

One of the most important issues in this era was the debate over systematic sampling, because of the heavy reliance on the line-plot and strip methods. Though earlier studies were concerned with this, Hasel (1938) conducted the first thorough study in forestry in regard to timber volume estimation and strongly advocated the randomization principals of R.A. Fisher in the case of heterogeneous populations, while at the same time stating that systematic cruises give closer estimates of the true volume than do random samples. Osborne (1942) conducted a similar study for mapping forest types and arrived at analogous conclusions about the nature of systematic surveys. Finney (1948), using Hasel's data and material from another fully enumerated forest, concluded that the increased precision obtainable from a systematic sample is seldom the sole reason to prefer it over stratified sampling. Finney noted, however, that "this argument would be destroyed" if one could develop a method for assessing the error from a simple, unique systematic sample. Finney's advice on stratification survives to the present, though many surveys continue to employ systematic methods without even the benefit of randomization of the initial sampling location, as suggested by Finney (1947).

Within the same period and subsequently, work on the theory for variance estimation in a systematic survey was greatly advanced by Matérn (1947, 1960, 1986). Since then, in the national forest inventories of Sweden and Finland, systematic cluster sampling design has been used (e.g. Kuusela and Salminen 1969). The ideas of Matérn were employed in assessing the precision of the inventory results (Salminen 1973, Ranneby 1981).

Another very important development in forest inventory was the introduction of sampling with unequal probabilities, namely the work of Bitterlich and Grosenbaugh, and the introduction of the use of an angle gauge to determine whether an individual tree is to be included in the sample. Angle gauge sampling quickly established itself as an efficient method of sampling forests for the characteristic that is of most interest to foresters — timber volume. Angle count sampling was first introduced by Bitterlich in 1947 and 1948, though its conception predated that by almost two decades (Bitterlich 1984, p. 3). Originally, it was envisaged by Bitterlich as a method for determining the basal area density of a forest by means of an angle gauge. The cruiser simply counts those trees whose diameter appears larger than the projected angle. It can be shown through simple geometric relations that each such tree represents a constant basal area per unit land area, and thus a simple count of trees on a 360° sweep of a sample "point" yields an estimate of the basal area in surroundings.

It was Grosenbaugh (1952, 1955, 1958), however, who extended this interpretation to the probabilistic sampling realm, developing a theory for estimating any quantity associated with the sample trees (e.g. volume, biomass, number of individuals) employing probability proportional to size (PPS) sampling methods. Grosenbaugh coined the term "point sampling" because it was in the relation of a randomly chosen point falling within a tree's inclusion area that this probabilistic argument was developed. Shortly afterwards, Palley and Horwitz (1961) gave a rigorous proof that point sampling was unbiased, while providing the statistical derivation of its design-based estimators under conditions of PPS sampling. While point sampling was a major innovation in sampling forests, where it is not feasible to visit every tree, many timber sales require just that.

Lacking in these methods is a generalized framework for estimating the components of forest growth. The continuous forest inventory system (CFI) introduced by Stott (1947) relied on permanent fixed area plots on which all the trees were numbered and remeasured annually. In time, methods like point sampling were also used in place of fixed-area plots, and annual remeasurements have largely given way to periodic 5- or 10-year visits. As the individual trees are numbered, the system allows tracking of each tree's growth and death over time. A second system, introduced to forestry by Bickford (1959) and more formally by Ware and Cunia (1962), optimally combines growth information from permanent plots with volume information from temporary plots. In sampling with partial replacement (SPR), only a portion of the plots that were originally established are remeasured, the rest being replaced with a sample of new plots. CFI can thus be thought of as a special case of SPR where all the plots are remeasured in each time period. SPR was adopted almost immediately by Bickford et al. (1963) in conjunction with double sampling for stratification for the forest survey in the northeastern U.S. and has proved to be an efficient design.

Apart from the work of Matérn (1960), the model-based approach has not been used extensively in forest inventories, although a few exceptions exist, e.g. the works of Mandallaz (1991), Kangas (1993) and Gregoire (1998).

Aerial photographs have also been used in forestry since the early 20th century, mostly for visual interpretation, but also for double sampling (Bickford

1952, see Chapter 14). In recent years information from satellite images has also been used, so that the national forest inventories in Finland and many other countries has become a multi-source inventory (e.g. Tomppo 1992, Bechtold and Patterson 2005, Chapters 11 and 12). Nowadays satellite images are gradually replacing the use of aerial photographs (Czaplewski 1999).

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MANAGING FOREST ECOSYSTEMS

Forest Inventory

Methodology and Applications

Edited by
Annika Kangas and Matti Maltamo

This book has been developed as a forest inventory textbook for students and can also serve as a handbook for practical foresters. The book is divided into four sections. The first section deals mostly with sampling issues. First, we present the basic sampling designs at a fairly non-technical mathematical level. In addition, we present some more advanced sampling issues often needed in forest inventory. Those include for instance problems with systematic sampling, and methods for sampling vegetation or rare populations. *Forest Inventory* also includes issues that are unique to forestry, like problems in measuring sample plots in the field, or utilising sample tree measurements. These issues include highly sophisticated methodology, but we try to present these also such that forestry students can grasp the ideas behind them. Each method is presented with examples. For foresters who need more details, references are given to more advanced scientific papers and books in the fields of statistics and biometrics.

Forest inventories in many countries involve much more than sampling and measurement issues. Most applications nowadays involve remote sensing technology of some sort, so that section II deals with the use of remote sensing material for this purpose. Examples of multi-phase and multi-source inventory are presented. Methods suitable for special applications, like stand-level or global-level inventory, are also presented. Section III deals with national inventories carried out in different parts of the world. Examples of forest inventory in selected countries around the world are presented. Section IV is an attempt to outline some future possibilities of forest inventory methodologies.

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