# Forest inventory

Charles T. Scott & Jeffrey H. Gove

Volume 2, pp 814–820

in

Encyclopedia of Environmetrics
(ISBN 0471 899976)

Edited by

Abdel H. El-Shaarawi and Walter W. Piegorsch

© John Wiley & Sons, Ltd, Chichester, 2002

# Forest inventory

Forest inventory is an accounting of trees and their related characteristics of interest over a well-defined land area. It may be compared to census methods for human populations. For example, one of the goals of the periodic decennial census of the US is to enumerate its human population and to retrieve demographic variables such as age, sex and race. This is accomplished by a comprehensive survey of all households in the country. Similarly, forest inventories seek to enumerate the population of trees within a forest and ascertain other information, such as their volume, value, growth and species composition. For all but the smallest tracts of land, complete enumeration of individuals is usually infeasible and survey sampling techniques are required.

Unlike human or animal populations, trees are sessile organisms and there is no immigration or emigration to consider. However, tree populations vary widely in their species composition, age, size, site requirements, potential value, longevity and growth – all factors that may influence the design of a forest inventory. In addition, the tree population of interest may exist over a wide variety of topography, making access potentially costly and sometimes even dangerous. Such variety often dictates sampling protocols that may be optimal only for some portion of the population in question. Alternatively, it may call for varying sampling intensity or strategy (the combination of the sampling design and associated estimators) between different regions within the population.

## Purpose

The prevailing reason for conducting a forest inventory is to make informed decisions about forest management. The primary need has been the quantification of volumetric product yield and structural composition of the forest. The volume of the timber resource is typically categorized by species, product and size. In addition, quantities like the number of trees and basal area per unit area are often desired. While collection of data on other components of the ecosystem is increasing, the timber resource still remains the main focus for most forest inventories.

Both spatial and temporal scales are normally addressed in the planning of an inventory. The most obvious dichotomy is in time: a forest inventory may be initiated for an assessment of current conditions (growing stock), or it may be repeated at future periods in time, yielding estimates of change in volume or basal area and possibly other components of growth, mortality and removals (due to harvest). Spatially, the size of the area in question may range from a small woodlot or individual stand to a national inventory. Not only are different methods required for differing spatial scales, but these inventories often are used to meet entirely different objectives. There are numerous reasons or objectives for conducting a forest inventory; the most common of these include:

- *Silvicultural prescriptions*: Inventories conducted in connection with stand examinations that focus specifically on making stand-level decisions over a short planning horizon of say 10 years with specific regard to the prescription of silvicultural treatments such as thinnings or regeneration harvests.
- *Regeneration surveys*: Assessing the adequacy of regeneration stocking following a regeneration treatment. Such efforts may be repeated to estimate survival rates.
- *Harvest or operational inventory*: Often required to more precisely estimate volume and value of an area prior to a commercial harvest. Postharvest inventories assess damage on residual trees and assess whether the amounts of remaining material conform to local laws and to the overall management plan.
- *Appraisal surveys*: Surveys conducted for the valuation of land and timber to be purchased, sold or exchanged.
- *Strategic inventories*: Large-scale inventories for forest-level strategic planning such as determining allowable harvest rates or optimal harvest scheduling plans.
- *Regional and national surveys*: Often mandated by law in the case of countrywide surveys, these inventories are commonly used for making high-level policy decisions and broad-scale resource monitoring. Surveys of this scale may also be augmented with other localized data to provide specific information, such as identifying a site for a new mill.

Although there can be some overlap between these various objectives, there are generally great differences among subsequent designs. For example, while

inventories for silvicultural prescription and operational inventories may both deal with the same stands, the objectives are different, and thus the intensity of the inventories will also differ. In the former case, sample information is collected at levels sufficient for informed decisions about the future management of the stands, while in the latter case, a detailed inventory, often entailing visiting every tree, may be required for precise estimates of volume and value.

## General Procedure

Once the objectives and the spatial and temporal scales have been determined, there are a number of other factors that must be considered when planning an inventory.

1. The sampling units and sampling frame must be identified. Depending on the design, the sampling frame may be viewed from either of two perspectives: land- or tree-centric. When every tree is visited (e.g. timber sales), the latter is the norm, while areal samples are used to select groups of trees within a known area in the land-centric approach.
2. The sampling strategy must be determined. This is closely tied to the previous and following points. It also encompasses the field methods, identification of inclusion probabilities, as well as the number of phases or stages and the estimators to be used (*see* **Sampling, environmental**). In addition, appropriate methods for computing tree component volumes (i.e. possibly by product class), if desired, must be determined; this will dictate, in part, the specific tree measurements required.
3. The area to be inventoried must be determined and a suitable map or remote imagery must be obtained for the ground survey. Where the sampling strategy is land-based, area delineation effectively determines the frame. If the area consists of more than one stratum, these must also be delineated. Here, strata may be any homogeneous land-based delineation of the tree population, such as stands, natural separations, or artificially determined boundaries. There are tradeoffs in making the choice of strata, e.g. stand boundaries are ephemeral and their change in time complicates subsequent inventory comparisons, but artificial strata often lack the connection to management decision and the homogeneity that stands afford.
4. The fixed and variable costs associated with the survey and precision at a given probability level should be established. Previous or pilot survey data for the area, or for similar areas, are used to estimate the variability of the key attributes of interest (normally volume or a closely correlated surrogate such as basal area). With this information, the sample size and plot design can be computed to meet the precision/cost objective.
5. The field instructions should be written. If available, portable data recorders can be programmed to collect and check data as it is entered. Data collection may include auxiliary information such as remotely sensed data (*see* **Remote sensing**). The data are then stored and edited.
6. A determination must be made as to the nature and final presentation of the information required from the inventory. The results must be assessed and interpreted to address the original questions and objectives of the survey. Careful consideration should be given to the presentation of the results so that they can be fully utilized by resource professionals. The survey itself should be evaluated to determine whether it has met the objectives, such as precision requirements, so that future surveys can be improved.
7. Finally, some quality control methods and quality assurance measures should be determined. Often, this will simply be in the form of a field guide or instructions and training for the cruisers. However, for many inventories, a certain percentage of the inventory is checked for accuracy by independent check-cruisers. Such may be the case for very valuable timber, or for inventories at the regional or national level.

The components in the list above are not independent of one another. For example, the target precision level, tree measurements, volume compilation methods and sampling strategy are all interrelated and due accord must be paid to this in the design phase.

## Forest Inventory Design

Forest inventory designs can range from very simple tree-based methods such as systematically sampling every $n$th tree encountered in a given area, to very complex multi-stage design and multiphase sampling

methods incorporating remote sensing and unequal probability sampling. A natural hierarchy to consider in discussing the design of forest inventories is (a) the overall design with respect to selection of sample units, and (b) the design of the individual sample units themselves and the method for selecting individual trees within these units. In the case of pure tree-based designs, the unit is the tree and only the first level in the hierarchy may be considered. However, it is worth mentioning that, while this two-level hierarchy is convenient for conceptualization, there may be other levels of subsampling employed within sample units, or on the individual trees themselves.

### *Sample Unit Selection and Inference Methods*

Forest inventories primarily rely upon design-based inference. However, **model-based inference** has been investigated and evaluated as an alternative method. Schreuder et al. [27] and Gregoire [8] give general overviews, while Kangas [19] and Schreuder and Wood [26] look at specific applications; Mandallaz [21] derives a unified theory for forest inventory from the model-based approach. Because design-based inference has dominated forest inventory, the classical approaches, such as simple random sampling and systematic sampling, commonly have been used for sample unit selection and subsequent estimation and inference. Sampling strategies have not been limited to equal probability designs, however, as the gains in using unequal probability sampling in forest surveys were understood early on [10, 11].

Auxiliary information for variance (and cost) reduction affects the design of a forest inventory in many ways. The simplest form is stratification: auxiliary information is used in the design phase to construct relatively homogeneous strata prior to ground sampling. Stratification typically uses remotely sensed imagery, such as aerial photography. Double sampling for stratification is a simple, yet practical example of the use of auxiliary information that was incorporated into the forest inventory and analysis (FIA) design for the northeastern US in the early 1960s [3].

A debate about the location of sample units started in the early part of the twentieth century when field sample units were laid out systematically. Hasel [18] strongly advocated **randomization** principles in heterogeneous populations, but stated that systematic cruises give closer estimates of the true volume than do random samples. Although Matérn [22] significantly advanced the theory for variance estimation in a systematic survey, estimators which appeal to simple random sampling designs are typically used because of their simplicity and because they generally are conservative.

### *Sample Unit Design*

**Areal-based Methods.** The design of sample units often takes the form of a geometrically compact area whose boundary is easily located on the ground. Areal-based sample units (usually referred to as plots) often contain many individual trees to be sampled. Benefits of such designs include the ability to estimate values on a per-unit-area basis, to gather sufficient information to characterize the area, and to concentrate the work effort (since travel time between sample units can be costly, especially in extensive inventories). Larger plots include more within-plot variation, thus reducing the between-plot variation. But, a larger plot means that fewer plots can be afforded, thus reducing the sample size. Such tradeoffs were recognized early on [6, 20, 30]. To further concentrate ground effort in one place, plot clusters are often used to advantage. For example, Scott [28] describes a design to provide for simultaneous optimization of different subplot types for different ecosystem components, such as soils, herbaceous vegetation and trees.

Two of the most widely used and easily implemented ground procedures involve the strip and line-plot cruising method for forest inventory. National inventories in Scandinavian countries employed systematic sampling with strips as early as the 1800s [31]. The strip method consists of sampling all trees in a strip of land with fixed width that extends between boundaries of the forest. Individual strips are laid out from a baseline and are systematically located to sample a fixed percentage of the forested tract. Line-plot methods similarly rely on the location of lines throughout the forest on which fixed-area plots are established at regular intervals. One of the early reasons to prefer the line-plot method to the strip method was that one could map the forest as changes in cover types were encountered while traversing the line, but spend less time sampling trees in the smaller plots. As aerial photography and other forms of remote sensing and **geographic information systems** (GIS) have come into regular use in planning

and implementing forest inventories, the need for accurate ground mapping along strips or lines has decreased.

One of the most influential developments in forest sampling is the areal-based method known as *plotless timber cruising*. Despite this nomenclature, which is accurate in the sense of fixed-area plots described above, this is indeed an area-based method, but the area is associated with each tree and is variable in size. Also termed *angle count sampling*, it was first introduced by Bitterlich in the late 1940s [4, 5]. With this method, an angle gauge can be used to estimate the density of basal area in the forest. The surveyor simply counts those trees whose diameter appears larger than the critical angle, $\alpha$, projected by the gauge (Figure 1, tree 'i'). Through geometric arguments, it can be shown that each such tree represents a constant amount of basal area per unit land area. Thus, a simple count of trees on a 360° sweep of a sample 'point' yields an estimate of aggregate basal area. Grosenbaugh [10, 11] extended Bitterlich's work by applying probability proportional to size (PPS) sampling methods to estimate any sample tree attribute (e.g. volume, **biomass**, number of individuals). Grosenbaugh coined the term *point sampling* because this probabilistic argument was based on the probability of a randomly chosen point falling within a tree's inclusion area. Subsequently, Palley and Horwitz [24] proved the design unbiasedness of the estimators derived by Grosenbaugh. The recognition that sampling was with probability proportional to tree basal area, which is highly correlated with tree volume, ensured early acceptance of point sampling.

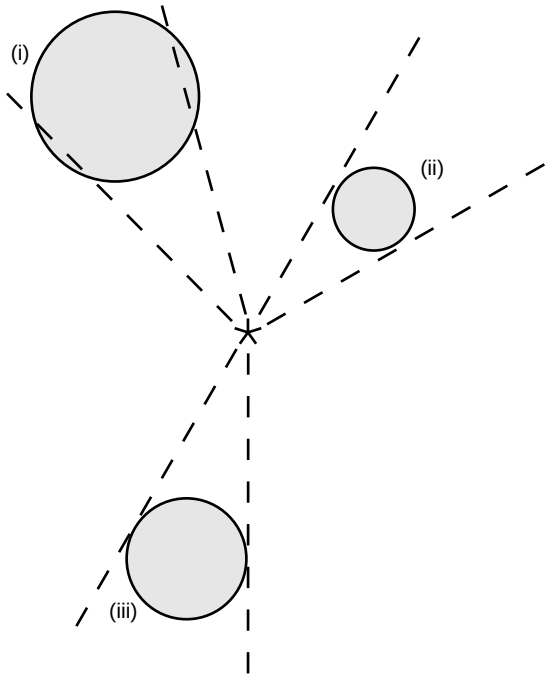


**Figure 1** In point sampling, a critical angle $\alpha$ (in minutes) is projected using a simple device such as an angle gauge or wedge prism (dashed lines). In case (i), if a tree's diameter appears larger than the critical angle it is sampled; in case (ii), if it appears smaller, it is disregarded; in case (iii), in the 'borderline' condition, measurements are taken to determine whether it is to be included in the sample or not

**Tree-based Methods.** Individual trees are often sampled for timber sales because reliable estimates of wood volume are required. As forested area increases, it becomes infeasible to measure every tree in detail, although visiting each tree to make a decision about whether it should be measured (sampled) or not remains reasonable. Such sampling is often conducted in the absence of a well-defined frame, because it is unusual to have a list frame of individual trees that collectively comprise the population of interest prior to sampling. Nor for large areas would such a listing be of much use.

In 1964, Grosenbaugh introduced *3P sampling* (probability proportional to prediction sampling) – a PPS method incorporating subjective volume predictions with detailed tree measurements for the estimation of volume in timber sales [12]. The sample size is random under this scheme, and sampling is concentrated on the trees of most interest (highest volume) due to the high correlation between predicted and actual volume for skilled cruisers. Grosenbaugh used 3P sampling as an efficient means of estimating tree volume by subsampling trees to take detailed tree measurements, like upper stem diameters, using sophisticated dendrometers. This procedure yielded unbiased estimates of tree volumes unlike the standard practice of relying on regional volume tables or equations.

Schreuder et al. [27] showed that 3P sampling is closely linked with Poisson sampling [16, 17] but was developed independently by Grosenbaugh. Two estimators of aggregate volume, termed the unadjusted and adjusted estimators, were originally proposed [13–15]. The unadjusted estimator is identical to the Horvitz–Thompson estimator (*see* **Sampling,**

**environmental**), which is quite imprecise owing to the random sample size feature of the sampling method. Grosenbaugh's adjusted estimator is recognizable as a generalized ratio estimator (*see* **Generalized regression estimators**), and is slightly design-biased but much more precise. Related work can be found in [9] and [33].

### *Sampling in Time*

While estimating current forest stocking and yield is an important objective in any forest inventory, estimating the components of forest growth is often equally important (*see* **Forest growth and yield modeling**). Three basic methods exist for change assessment: (a) independent inventories with different sample units taken at two different time periods, (b) the same sample units remeasured at both occasions, or (c) some combination of remeasured and independent units. Schreuder et al. [27] refer to these as 'complete replacement', 'complete remeasurement', and 'partial replacement', respectively.

In forestry, Stott [32] formalized the concept of complete remeasurement in the context of fixed area plots and called it *continuous forest inventory* (CFI). All trees on CFI plots were numbered to track individual tree growth, development and death (or harvest) over time. Trees growing into the smallest diameter size class measured (termed 'ingrowth') are also typically recorded in CFI inventories. Today, CFI plots are normally remeasured on a 5- to 10-year cycle.

Sampling with partial replacement (SPR) was first introduced to forestry by Bickford [2] and then expounded more fully by Ware and Cunia [35]. SPR optimally combines growth information from permanent (CFI) plots with information from newly established plots. The forest survey in the northeastern US adopted SPR almost immediately [3]. SPR is flexible and efficient for estimating both components of change and current yields. The SPR estimators for two occasions were extended to the multivariate case by Newton et al. [23], while Van Deusen [34] reformulated the estimation of both current volume and components of growth using generalized least squares. Van Deusen also showed how constraints could effectively be included in the estimation scheme to ensure additivity of growth components, for example. Scott and Köhl [29] extended these results to include stratification on multiple occasions.

### *Sampling Near the Forest Edge*

A very practical concern in forest inventories is the sampling of trees that lie near the forest boundary, because part of their inclusion area lies outside the tract. The probability of including such trees in the sample is diminished because of the smaller area inside the boundary. Arguably, the most practical method of handling the **edge-effect** bias is the mirage or reflection method developed by Schmid-Haas [25] and introduced to the North American literature by Beers [1]. The mirage method is design unbiased [7] and can be extended to other attributes, such as coarse woody debris.

### *Synopsis of Related Methods*

As mentioned earlier, forest inventories have focused on estimation of the volume and stocking parameters. Thus, considerable research on individual tree volume estimation methods has been conducted. In addition, many inventories have employed sophisticated multiphase designs incorporating layers of remote sensing media and GIS databases. In recent years, forest inventory has shifted to **ecosystem monitoring**, where many attributes including soils, other vegetative strata, dead trees and down **coarse woody debris** are observed. Ecological **biodiversity** and forest health have become major concerns. New methods have been developed to address these issues, but much work is still required as the nature of forest inventory continues to evolve.

### *References*


[1] Beers, T.W. (1977). Practical correction of boundary overlap, *Southern Journal of Applied Forestry* **1**, 16–18.

[2] Bickford, C.A. (1959). A test of continuous inventory for national forest management based upon aerial photographs, double sampling, and remeasured plots, in *Society of American Foresters Proceedings*, Society of American Foresters, Bethesda, pp. 143–148.

[3] Bickford, C.A., Mayer, C.E. & Ware, K.D. (1963). An efficient sampling design for forest inventory: the northeastern forest resurvey, *Journal of Forestry* **61**, 826–883.

[4] Bitterlich, W. (1947). Die Winkelzählmessung, *Allgemeine Forst- und Holzwirtschaftliche Zeitung* **58**, 94–96.

[5] Bitterlich, W. (1948). Ein neues Messverfahen zur Aufnahame stehender Holzmassen, *Österreichs Forst- und Holzwirtschaft* **3**, 89–90.

[6] Bormann, F.H. (1953). The statistical efficiency of sample plot size and shape in forest ecology, *Ecology* **34**, 474–487.

[7] Gregoire, T.G. (1982). The unbiasedness of the mirage correction procedure for boundary overlap, *Forest Science* **28**, 504–508.

[8] Gregoire, T.G. (1998). Design-based and model-based inference in survey sampling: appreciating the difference, *Canadian Journal of Forest Research* **28**, 1429–1447.

[9] Gregoire, T.G. & Valentine, H.T. (1999). Composite and calibration estimation following 3P sampling, *Forest Science* **45**, 179–185.

[10] Grosenbaugh, L.R. (1952). Plotless timber estimates – new, fast, easy, *Journal of Forestry* **50**, 32–37.

[11] Grosenbaugh, L.R. (1958). Point-sampling and line-sampling: probability theory, geometric implications, synthesis. Southern Forest Experiment Station Occasional Paper 160.

[12] Grosenbaugh, L.R. (1963). Optical dendrometers for out-of-reach diameters: a conspectus on some new theory, *Forest Science Monographs* **4**, 1–47.

[13] Grosenbaugh, L.R. (1964). Some suggestions for better sample-tree-measurement, Proceedings Society of American Foresters Annual Meeting, 20–23 October 1963, Boston, pp. 36–42.

[14] Grosenbaugh, L.R. (1965). Three-pee sampling theory and program THRP for computer generation of selection criteria. USDA Forest Service Research Paper PSW-21.

[15] Grosenbaugh, L.R. (1976). Approximate sampling variance of adjusted 3p estimates, *Forest Science* **22**, 173–176.

[16] Hájek, J. (1958). Some contributions to the theory of probability sampling, *Bulletin of the Institute of International Statistics* **36**, 127–134.

[17] Hájek, J. (1964). Asymptotic theory of rejective sampling with varying probabilities from a finite population, *Annals of Mathematical Statistics* **35**, 1491–1523.

[18] Hasel, A.A. (1938). Sampling error in timber surveys, *Journal of Agricultural Research* **57**, 713–736.

[19] Kangas, A. (1994). Classical and model based estimators for forest inventory, *Silva Fennica* **28**, 3–14.

[20] Lindsey, A.A., Barton, J.D. & Miles, S.R. (1958). Field efficiencies of forest sampling methods, *Ecology* **39**, 428–444.

[21] Mandallaz, D. (1991). A unified approach to sampling theory for forest inventory based on infinite populations and superpopulation models. Doctoral thesis no. 9378, Chair of Forest Inventory and Planning, Department of Forest and Wood Sciences, ETH-Zentrum, CH-8092 Zürich.

[22] Matérn, B. (1986). *Spatial Variation*, Lecture Notes in Statistics, Vol. 36, Springer-Verlag, New York.

[23] Newton, C.M., Cunia, T. & Bickford, C.A. (1974). Multivariate estimators for sampling with partial replacement on two occasions, *Forest Science* **20**, 106–116.

[24] Palley, M.N. & Horwitz, L.G. (1961). Properties of some random and systematic point sampling estimators, *Forest Science* **7**, 52–65.

[25] Schmid-Haas, P. (1969). Stichproben am waldrand, *Mitt Schweiz Anst Forst Versuchwes* **45**, 234–303.

[26] Schreuder, H.T. & Wood, G.B. (1986). The choice between design-dependent and model-dependent sampling, *Canadian Journal of Forest Research* **16**, 260–265.

[27] Schreuder, H.T., Gregoire, T.G. & Wood, G.B. (1993). *Sampling Methods for Multiresource Forest Inventory*, Wiley, New York.

[28] Scott, C.T. (1993). Optimal design of a plot cluster for monitoring, *The Optimal Design of Forest Experiments and Forest Surveys*: Proceedings, IUFRO S.4.11 Conference, K. Rennolls & G. Gertner, eds, University of Greenwich, London, pp. 233–242.

[29] Scott, C.T. & Köhl, M. (1994). Sampling with partial replacement and stratification, *Forest Science* **40**, 30–46.

[30] Smith, H.F. (1938). An empirical law describing heterogeneity in the yields of agricultural crops, *Journal of Agricultural Science* **28**, 1–23.

[31] Spurr, S.H. (1952). *Forest Inventory*, Ronald Press, New York.

[32] Stott, C.B. (1947). Permanent growth and mortality plots in half the time, *Journal of Forestry* **45**, 669–673.

[33] Van Deusen, P.C. (1987). 3-p sampling and design versus model-based estimates, *Canadian Journal of Forest Research* **17**, 115–117.

[34] Van Deusen, P.C. (1989). Multiple-occasion partial replacement sampling for growth components, *Forest Science* **35**, 388–400.

[35] Ware, K.D. & Cunia, T. (1962). Continuous forest inventory with partial replacement of samples, *Forest Science Monographs* **3**, 1–40.

(*See also* **Forestry**; **Habitat sampling**; **Spatial design, optimal**; **Spatial analysis in ecology**)

CHARLES T. SCOTT & JEFFREY H. GOVE