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Insect Pests *see* **Entomology**: Bark Beetles; Defoliators; Foliage Feeders in Temperate and Boreal Forests; Population Dynamics of Forest Insects; Sapsuckers. **Health and Protection**: Integrated Pest Management Practices; Integrated Pest Management Principles. **Tree Breeding, Practices**: Breeding for Disease and Insect Resistance.

Integrated Pest Management *see* **Entomology**: Population Dynamics of Forest Insects. **Health and Protection**: Integrated Pest Management Practices; Integrated Pest Management Principles.

INVENTORY

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Forest Inventory and Monitoring

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Introduction

Decision-making processes require sound and reliable information. This assertion is well borne out in forest science, indeed in the practice of forestry, where decision-making must rest on many sources of information, all of which ultimately recognize the need to manage forestry resources wisely over long periods of time. Forest inventory and monitoring is an essential means of obtaining this information and is a basic component of the cycle of procuring information, decision-making, and control of operations.

Forest inventories offer a bundle of instruments, which provide decision-makers with a wide range of sound and reliable information concerning the forestry sector. Forest inventories utilize expertise from different fields such as sampling theory, surveying, information technology, remote sensing, geographical information systems, mensuration, or modeling.

In the following article a general introduction to inventory and monitoring forests will be given. This overview covers inventory concepts, attributes assessed, data sources, categories, and work phases of forest inventories.

Inventory Concepts

Sampling Designs

Due to cost and time constraints a full tally of forests must be ruled out and is generally replaced by sampling techniques. The use of statistical sampling techniques can be traced back to a period in the early nineteenth century that also witnessed the formation of statistical societies in Europe and North America. About 150 years ago the Danish forest service conducted a nationwide census of forests, which can be seen as the first national forest survey. About 1850, Brandis introduced strip surveys in Burma at 5% intensity for inventory and management. Linear strip samples were used in Sweden as early as in the 1840s. In the 1920s Swedish forests were assessed at a national level by measuring strips from the coast to the Norwegian border across the country and deriving estimates for the entire nation.

In the eighteenth and the beginning of the nineteenth century methods were developed that were based on the visual assessment of forest stands. In the nineteenth century a shift from fuel-wood to high-quality timber production forced a change in monitoring methods. Visual assessments were replaced by measurements and censuses of the quantity of standing timber. The German forest commissioner Schmidt wrote in 1891:

> *Unfortunately is this assessment method (i.e. the census) especially in dense stands time consuming and expensive, and one replaces it often and with pleasure by the plot assessment method. It is a known fact that hereby a conclusion is made from a part of the stand to the entire stand.*

Schmidt notes that the (rectangular) plots should be placed in those parts of the stand which represent the entire stand. According to Schmidt it is difficult to decide which plot design is suitable in heterogeneous stands to represent the entire stand, and that one can solve this 'embarrassing situation' by selecting several plots in different parts of the stand. He concludes that 'one comes the closer to the truth the more plots are selected.' In spite of a knowledge of statistical theory, Schmidt utilizes two major principles of sample survey: representativeness and replication.

As the tools of statisticians to collect, analyze, and draw inferences from data continued to expand in the twentieth century, forest research moved along to set statistical principles in the framework of forest resource assessments and to use those tools to understand better both the ecology of forests on local, regional, and global scales, as well as the environmental impact of forest management at these scales. In the 1930s sampling of forests started in North America. A lack of forest maps and limited knowledge about extensive forest resources gave rise to inventory techniques that were very different from those used in Europe at that time. Survey sampling in a sound statistical manner was first reported by Hasel in 1942.

A driving factor in developing sample-based inventory systems was the need to provide for cost-efficient methods for forest resource assessments. The general principle of sampling is to select a subset of elements (i.e., a sample) from a population, to measure this subset intensively, and to draw inferences from the sample to the entire population (**Figure 1**). Statistical theory is applied for the selection process by assigning each population element a (known) selection probability. The selection probability is then utilized for the inference process.

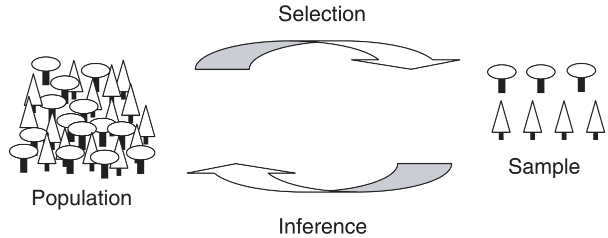

Figure 1 The concept of statistical sampling.

An outstanding number of sampling designs for natural resource assessments has been presented in the literature. They can be divided into two main groups: (1) sampling designs without utilization of auxiliary information, and (2) sampling designs utilizing auxiliary information. In sampling designs without auxiliary information, only observations on the attributes of interest that are obtained from population elements selected by the sample are used for inference. As, apart from the sample, other information about the population is often available or can easily be obtained, e.g., from aerial photography or satellite imagery, designs have been developed in which such information is used in estimation procedures. As a rule, sampling designs with auxiliary information are more efficient than those without. The major types of sampling designs with and without auxiliary information are presented in **Figure 2**.

Sampling Units

Before selecting a sample the population must be divided into parts that are called sampling units. The sampling units applied in forest resource assessments are single trees only in exceptional cases. In order to reduce assessment efforts and costs, groups or clusters of trees are selected. The clusters can be formed by selecting at each sample location a fixed number of trees (so-called nearest-neighbor or *n*-tree methods), or all trees that are located within an area of fixed shape and size, i.e., circular, squared, or rectangular plots (**Figure 3**). These alternatives assign a constant sampling probability to each tree. Typical plot areas are between 100 and 700 m^2. As stand density is related to tree size, large-area plots can result in

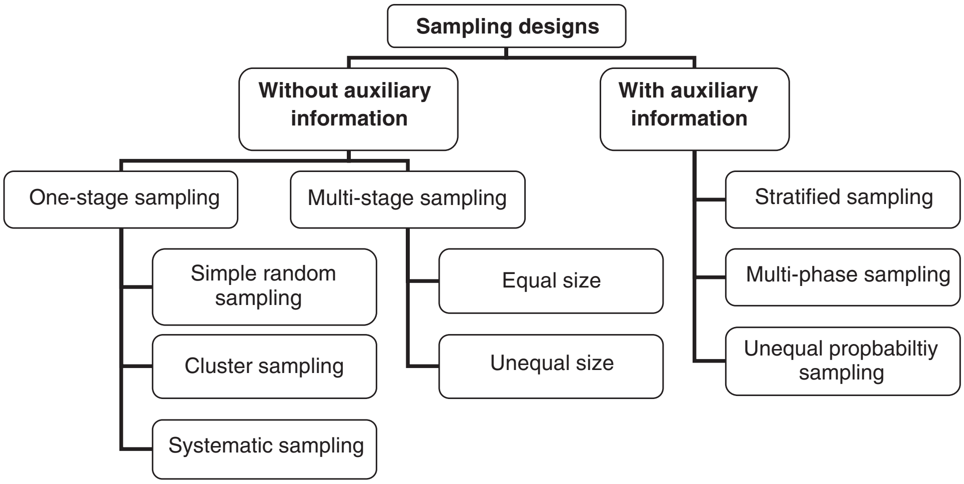

Figure 2 Sampling designs.

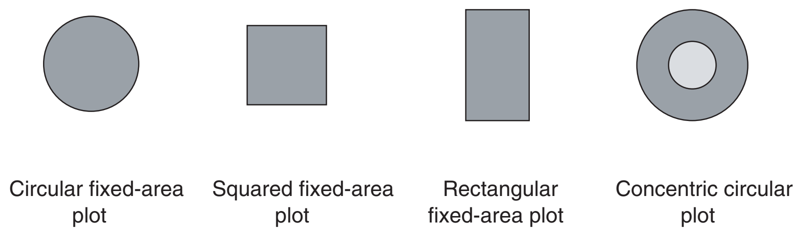

Figure 3 Fixed-area plots.

situations where a large number of trees (e.g., >100 trees) with small dimensions are located on a sample plot. To reduce the number of selected small trees and to increase cost-efficiency, concentric plots can be applied; these are a cascade of plots with different areas. On the smallest plot all trees are selected while for the larger plots only trees with larger thresholds of minimum diameter at breast height (dbh) are considered. For example, the Swiss national forest inventory utilizes two concentric sample plots with sizes of 200 m^2 and 500 m^2. On the smaller plot all trees are selected while on the larger plot only those trees with a dbh above 35 cm are selected.

Where the sampling probability of a tree is proportional to some tree attribute, the selection incorporates unequal probability sampling, e.g., probability proportional to size (PPS) or probability proportional to prediction (PPP). The most widely used unequal probability sampling approach in forest inventories is point sampling (also known as plotless sampling, angle count sampling, or Bitterlich sampling), where trees are selected with a probability proportional to their dbh (**Figure 4**). The selection procedure is realized by viewing all trees visible from a randomly chosen sample point within a forest by a constant angle. Those trees appearing larger than the constant angle are selected as sample trees. As a tree with a large dbh can be further apart from the sample point to be included in the sample (i.e., appears larger than the constant angle) than a tree with a smaller dbh, the procedure assigns a sampling probability proportional to the size of the dbh.

The selection of the optimal sampling design for a specific assessment program is an iterative process that is driven by the required information needs, the available resources, cost-efficiency, and the desired reliability of the information to be provided.

Monitoring Change by Sampling at Successive Occasions

The idea of describing the development of stands through permanent observations and thereby controlling the sustainability of forest management was born in the nineteenth century. In the 1930s, sampling methods, known as continuous forest inventory (CFI), were developed which were based on repeated measurements of a set of sample plots. With the CFI method, all sample plots, which are measured at the initial occasion, are measured again in successive inventories. Changes can be quantified by calculating the difference of estimates on two successive occasions.

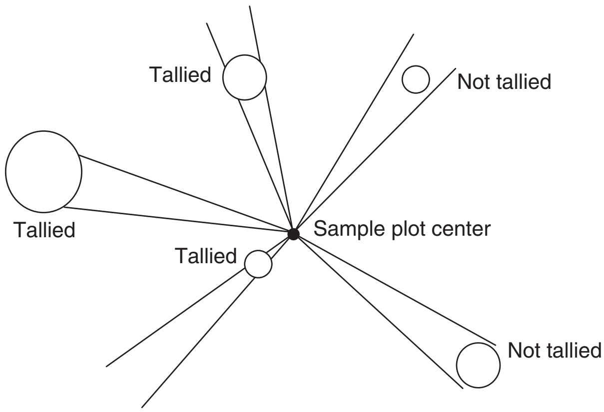

Figure 4 The principle of point sampling.

Remeasured plots are called permanent plots and are established at the first occasion by registering the plot location as well as the position of the trees inside the plots. Permanent plots can be realized by fixed-area plots, point samples (Bitterlich plots), or nearest-neighbor methods. As the location of each sample tree is known, it is straightforward to describe the individual tree history and thus the growth components formed by survivor trees, ingrowth, mortality, and cuts.

The application of the CFI method over long periods of time may lead to problems caused by its rigid system of permanent plots. An initial set of plots may lack representativity when plots are lost, e.g., by disturbances or land use changes, or cannot be relocated in the course of time. When inventory objectives are changing over time, it may become necessary to establish additional plots at new locations. However, the statistical estimation procedures used with CFI are straightforward and can be understood intuitively.

A sampling method for field surveys that was introduced into forest inventory in the 1960s is sampling with partial replacement (SPR). With this method, part of the sample plots that are measured at one occasion are replaced by new sample plots at the next occasion (**Figure 5**). For two occasions three types of sample plots are obtained:

1. Sample plots, which are measured at time 1 as well as at time 2 (permanent sample plots, matched plots).
2. Sample plots, which are only measured at time 1 (unmatched plots).
3. Sample plots, which are only measured at time 2 (new plots).

SPR is a flexible design with several advantages. It is possible to replace lost plots and to allocate new plots according to changes of inventory objectives.

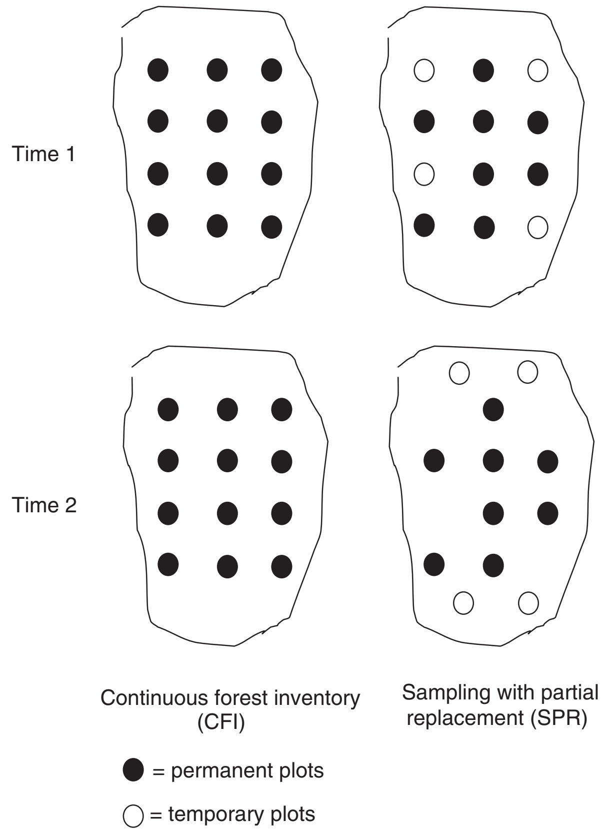

Figure 5 Sampling at successive occasions.

The number of unmatched and new plots does not necessarily have to be the same. By adjusting the proportion of new and matched sample plots it is possible to optimize cost-efficiency according to the focus on current state or changes. If only current state is to be considered, temporary sample plots often prove to be more cost-effective than permanent plots, since the expenditures for marking the sample plot centers and the registration of sample tree coordinates do not exist. However, permanent plots result in precise change estimates. A major disadvantage of SPR is that the estimation procedures become unwieldy and deterrent after more than two occasions.

Besides CFI and SPR, other approaches have been described to assess changes. Those approaches include independent assessment at each occasion, updating observations by modeling, or a combination of a low number of permanent plots and extrapolation of past observations by modeling.

A Typology of the Attributes Assessed

The sampling concepts described above determine the procedure by which the sample is selected from the populations. Once a sample has been selected, attributes are assessed at the individual sampling units. Attributes assessed in forest inventories can be related to individual trees or to areas such as the site or the stand. Only a limited number of attributes can be directly measured, such as tree height, diameters at different stem heights, crown length, bark thickness, bole length, basal area, or thickness of the humus layer. From a statistical perspective those attributes are observed on interval or absolute scales and allow for the computation of a variety of statistical parameters (e.g., mean, variance, standard deviation, coefficient of variation, median, or coefficient of correlation). A large set of attributes is assessed according to definitions, e.g., tree species, crown shape, defects, diseases, tree layer, soil type, development stage, or management activities. As those attributes are nominal or ordinal-scaled, they only allow for a limited number of statistical parameters (e.g., median, mode, range, or proportion). Attributes directly assessed can be used as input variables for models and form the base for a large set of derived attributes. Among those are, for example, stem volume, above-ground tree biomass, assortments, timber value, species mixture proportions, and site class.

Data Sources

The major data sources utilized by forest inventories are *in-situ* assessments. Attributes that cannot be assessed by field visits, such as ownership, past management activities, or investments in infrastructure, render data assessment by questionnaire necessary. Despite the fact that the location where data are assessed may be georeferenced, it is not possible to derive spatially explicit data (i.e., maps) from those data. The visualization of results in mapped format is restricted to the spatial resolution of the units of reference.

Since the beginning of the 1920s the use of aerial photography for forest resource assessments has been studied. The development of operational remote sensing techniques in the 1970s added a new data source to traditional information gathering. Remote sensing imagery provides wall-to-wall maps of land cover and forest types for entire inventory areas and allows for spatial analyses. However, the number of attributes that can be derived from remote sensing data is limited. The combination of remotely sensed and *in-situ* data by statistical approaches offers the potential to utilize both the depth of the thematic information of *in situ* assessments and the spatially explicit information of remote sensing data.

Beside field data, questionnaires, and remote sensing data, other data sources are utilized for forest inventory purposes. Among those auxiliary data are statistics, e.g., on population, timber markets, or economy, and thematic maps displaying topography, geomorphology, administrative boundaries, transport systems, climate, or location of settlements and industries. The availability of geographic information systems and their capability to handle spatially explicit data layers offer powerful tools for spatial analyses and spatial modeling.

Information Needs

Long-term sustainability motivated forest scientists to seek methods to monitor and predict the long-term development of forests. The principles of sustainable forest management were developed in times when public demands concerning forests concentrated on the production of timber. Thus traditional inventory and monitoring methods mainly focused on the balance of timber growth and timber utilization. During the past decades sustainability became a prominent concern in the entire environmental context. In the context of sustainable development forests are no longer seen solely as a timber resource, making sustainable forest management, according to the Intergovernmental Panel on Climate Change, 'a system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological (including biological diversity), economic and social functions of the forest in a sustainable manner.'

In order to meet today's information needs the methodological background of forest inventories has been significantly widened in the past decades and allows information to be provided on the multiple wood and nonwood goods and services of forests. Forests are not solely treated as management systems but as a holistic concept subject to multiple ecological, economic, and social relationships. Sustainable forest management requires the observation of forests in successive points in time. Forest inventories thus provide tools to assess current information as well as information on changes. A set of successive forest inventories is often called a forest-monitoring system.

Decision-making in the forestry sector is realized at different levels and thus requires information for different spatial scales. Forest management planning has a high demand of spatially explicit, local information, while decisions at a political level render information aggregated to the regional or national scale necessary. National information can be cumulated on a multinational, continental, or global level and form the information base for multinational programs and initiatives. The vertical aggregation from task-specific to integrative and

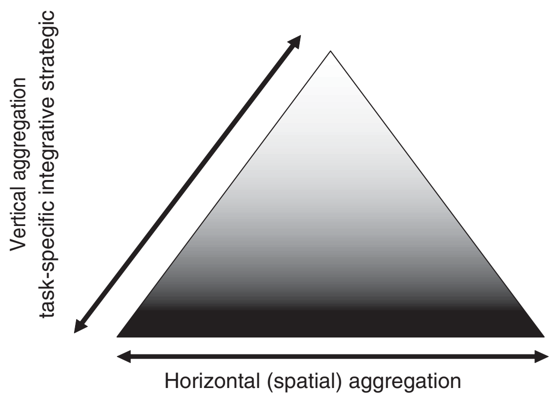

Figure 6 Horizontal and vertical aggregation of information.

strategic planning goes hand in hand with spatial (horizontal) aggregation, resulting in an increasing area of units of reference for which information is provided (**Figure 6**).

In the context of sustainable forest management, forest resource assessments may provide information on the current state and changes over time on the following thematic aspects:

- forest resources, including forest area and growing stock
- carbon balance
- health and vitality of forest ecosystems
- productive functions, including growth and harvested timber
- biological diversity
- protective functions
- socioeconomic functions and conditions.

For specific questions such as scenic beauty, forest ecology, or potential forest habitats, it can be necessary to study forests in a landscape context, rendering spatially explicit information of the location of forested land necessary.

Categories of Forest Inventories

According to the inventory objectives and the size of the area to be surveyed, different categories of forest inventories can be defined. Forest inventories are for the most part realized as multipurpose resource inventories and aim at an ample picture of the multiple functions provided by forests.

Global forest inventories are conducted to determine forest resources at a global level and were compiled by the Food and Agriculture Organization several times since 1946. Global forest resource assessments utilize existing national data to a maximum extent. As national assessments are aiming at specific national or regional information needs, they do follow individually designed inventory concepts and systems of nomenclature. Much discussion and readjustment of the results of national forest inventories is necessary before they can be compiled to give a global picture. Advances in remote sensing techniques allow satellite imagery to be applied to determine the distribution of forest vegetation throughout the world.

National forest inventories are already being conducted in many countries, especially in temperate and boreal regions. In Scandinavia national forest inventories have been running since the 1920s. Timber volume is usually employed as a key parameter, though information on the distribution of forested areas, the condition of the forest, and productivity also has to be collected. The non-wood functions of the forest are receiving increasing attention. Ideally, national inventories are planned as permanent surveys with periodic updates. Information obtained through national inventories is mainly applied in questions of national forest policy and international commitments and initiatives.

Land-use inventories extend the concept of forest resource assessments to other types of land use. Aerial photographs and satellite data are of especial importance here. In the scope of UN Framework Convention on Climate Change (FCCC) land use, land use change and forestry (LULUCF), land use inventories are a major tool in quantifying carbon sinks and sources.

The term ‘regional forest inventory’ is applied to a variety of inventories. Regional forest inventories register only a subset of the national forested area or an area which is assembled by two or more countries. The size of the area covered by regional forest inventories usually comprises between 50 000 and some hundreds of thousands of hectares. Similarly to national inventories, they are intended to provide a general picture of the situation regarding forestry. In a global framework the term ‘regional forest inventories’ is used to describe inventory areas that cover entire continents, parts of continents, or forest vegetation zones. Similar to global forest inventories, data available at the national level are utilized to a maximum extent.

Stand level inventories are the most intensive type of forest inventory and aim at detailed information for forest-planning purposes on individual stands and on intensively managed but restricted areas. Usually the data are computed on a stand-by-stand basis for each species. Information on increment, detailed forest maps, and data on the quality of the various sites are just as necessary as details on topography, ownership, and accessibility. As an integrated part of sustainable forest management, stand level inventories are normally realized as permanent inventories.

Reconnaissance inventories provide a rough insight of forest characteristics of a limited area. As well as the location and extent of forested areas, they register accessibility, species composition, tree dimensions, the distribution of various forest types, and initial data on timber quality and forest ecology. As reconnaissance inventories are conducted at minimum cost, the employment of remote sensing data is promoted while field surveys are restricted to the minimum. They frequently serve for the preparation of an intensive forest inventory by providing basic information on the degree of variation of forest attributes.

Exploitation surveys, logging plan surveys, and wood procurement studies are conducted to provide a basis for the planning of timber-harvesting operations. The main focus is on determining the current state of standing crop, classified according to species, dimensions, and assortments. Information on accessibility can be included in nonopened-up areas. Information on increment, sustainability, or ecological conditions is not in the focus of such inventories.

Forest health monitoring became prominent in European countries in the 1980s when forest decline was a public concern. In Europe and North America such surveys are conducted regularly in order to track the course of development of different types of damage. Among the attributes assessed are crown transparency, needle and leaf discoloration, regeneration, and mortality.

The typology of forest inventories described above does not represent a rigid classification scheme. Special surveys may be conducted to satisfy individual information needs. For instance, the assessment of current state and changes of woody biomass can be a major concern for carbon budgeting. The various types of forest inventories may overlap and increasing demands for information on nonwood goods and services and biological diversity may lead to new inventory types.

The Work Phases of Forest Inventories

The planning of forest inventories is a complex task that brings together experts with different technical backgrounds. The time span between the expression of the need for a forest resource assessment and the availability of inventory results may easily cover a decade. In order to plan and organize a forest inventory the proven rules of system analysis and project management are to be followed. Carrying out a forest inventory can be divided into four main work phases:

1. Definition of the inventory objectives and the information desired.
2. Development of the sampling design, the sampling methods, and the concept for data analysis.
3. Data assessment (field surveys, remote sensing data analyses, and collection of information in other data sources).
4. Data analyses and publication of the results.

See also: **Inventory**: Large-scale Forest Inventory and Scenario Modeling; Modeling. **Mensuration**: Forest Measurements; Growth and Yield.

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