Statistical strategies for combining existing information also need to be strengthened. There is a wealth of data available, but how can we combine it, compare it, and disaggregate the information?

Finally, we need more research on integrated analyses to determine how changes in one resource will affect other sectors. For example, forest land is increasing in many parts of the developed world as agricultural lands are abandoned. Does this reduction of agricultural lands in the north increase deforestation in the developing world as lands are converted to agriculture?

Summary

Agencies such as the USDA Forest Service are taking an integrated approach to developing inventories. Inventories concentrate on measuring basic resource attributes in a manner that will permit multipurpose interpretations.

Cooperation and coordination, standardization, objectivity, and control and responsibility are fundamental in designing these inventories to ensure that the inventories can be summarized and used by decision-makers for a variety of purposes.

See also: **Biodiversity**: Biodiversity in Forests. **Inventory**: Forest Inventory and Monitoring. **Mensuration**: Forest Measurements. **Resource Assessment**: Forest Resources.

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Stand Inventories

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Introduction

Stand inventories are the classical way to build a management plan. The first step is the delineation of stands: useful for this are forest survey, aerial photography, or remote sensing technologies (*see* **Resource Assessment**: GIS and Remote Sensing). The second step is to collect information on each stand. This can be done by using inventory techniques (sampling techniques) or by using aerial photographs or remote sensing. In the future, a new approach could bring better results: airborne laser-scanning combined with high resolution satellite data, for example.

This article covers special stand inventory techniques based on considerations of precision and accuracy and tries to demonstrate the differences between stand inventories and forest inventories.

Historical Overview

The classical method to obtain data for a management plan is to use stand inventories. After the stands have been delineated, some information on each of them is collected. See **Table 1** for an actual example from the nineteenth century.

Table 1 An example from the nineteenth century of classical stand inventory, transformed, simplified, and translated from the method of Judeich

Stand number	*Area (ha)*	*Tree species*	*Age (years)*	*Volume ($m^3 ha^{-1}$)*		*Site class*	*Crown closure*
				Coniferous	*Deciduous*		
20a	3.03	8 spruce, 2 fir	79	400	–	3	0.8
20b	2.25	4 spruce, 3 fir, 3 beech	65	180	70	1	0.8
20c	5.06	10 spruce	5	–	–	1	–
20d	4.50	8 beech, 2 spruce	125	50	500	4	0.7

The stand borders were measured with a tape and a compass. The stand area was taken from maps using planimetric techniques. The stand age was derived from older information or by counting tree rings or whorls in younger stands. Tree species composition and crown closure were ocular estimations. The volume per hectare was estimated ocularly or measured by complete enumeration. Finally, the site class (relative yield class) was determined from yield tables using the age and the volume per hectare. These tables were only used to estimate the volume increment and the 'normal' volume (mean volume of a full stocked stand over a complete rotation).

In those days all information such as allowable cut and rotation length were derived from these data. Today stand inventories are more sophisticated, using a wide range of different estimation methods. Forest inventory covers the need for strategic information, and involves surveying the whole forest enterprise area with designed sampling and measuring techniques. Stand inventories are used to obtain area (stand) related data. This data collection is problem oriented and these data should form the database for decision support systems.

Stand Inventory Techniques

Ocular Estimation of Volume

This method is very crude, because the quality of obtained data is dependent only on the experience of the person doing the estimating. Precision (confidence interval at 5% level) has been reported from $\pm 31\%$ to $\pm 38\%$ and bias from 4% to 20%. This method is quick and cheap but neither the precision nor the accuracy are reliable.

Yield table estimation using dominant height, age, and ocular-estimated crown closure to determine the stocking degree An investigation of 1221 sample points showed a standard error of estimation of $\pm 27\%$ (calculating a regression between stocking degree and crown closure) but no bias. The results of this method will not be better than the results of ocular estimation alone.

Sampling techniques to measure the basal area In this case the basal area will be estimated using simple point sampling (counting only the trees) without control of borderline trees. The omission of these trees could introduce a bias (in one example we found a bias of 18% and a confidence interval at 5% level of $\pm 16\%$). On the other hand the trade-off is that you need an appropriate yield table to estimate the volume – this is not true – only the form factor and the relation between dominant height and mean height will be used from the yield table.

Complete Enumeration Methods

Measuring all diameters This technique consists in measuring the diameter at breast height (dbh) of all trees in a stand and to record this in dbh classes (this can be also done by using special callipers with scales divided into 4-cm or 5-cm classes). As height measurement is time consuming, the height will only be measured on a subsample of trees (not smaller than 20 trees per stand).

Theoretically, this method should be error-free for the number of trees and the basal area. The error of the volume estimate will be inflated by height measurement error. During field camps students have applied this technique on 28 different stands with an area of ~ 1 hectare. A week later other students have measured the same stands. From these data the confidence interval at 5% level was calculated giving $\pm 4\%$ for the number of trees, $\pm 5\%$ for the basal area and $\pm 11\%$ for the volume. The confidence interval is strongly dependent on the sighting visibility condition in the stand: in pure stands without shrubs and regeneration the confidence interval is significantly smaller than in mixed stands with more layers, shrubs and regeneration. The minimum confidence interval found was $\pm 2\%$ and the maximum confidence interval found was $\pm 9\%$ for the number of trees.

Another reason for error could be the use of a minimum diameter – excluding the smallest dbh class from the above-mentioned data reduced the confidence interval to $\pm 3\%$ for the number of trees.

The higher confidence interval for the basal area can be explained by a diameter measurement error of

0.8–1.0 cm, which is approximately double the reported errors in the forest inventory. In complete enumeration the measurement instruction for dbh: ('on the hillside, 1.3 m above ground, direction downhill') cannot be carried out because it is too time consuming.

Complete enumeration with dbh measurement gives precise and accurate stand data and information on texture and structure. The stand area is not needed for the estimation, but this can be sometimes helpful. This technique is time consuming, with the investigation time being strongly correlated with the number of trees. This method can only be recommended for older stands of special interest.

Using ocular estimates of tree volume This method is an application of '3P' sampling techniques (sampling with probability proportional to prediction). The preliminary steps are:

1. Define either an average volume per tree in the stand (this is similar to the choice of the basal area factor (BAF) using point samples) or define a certain number of trees to be measured. In this case we need also an estimate of the stand total volume (ocular estimation or from an older management plan). The average volume per tree in the stand is obtained by dividing the stand total volume by the number of trees.
2. Create a list of equal distributed random numbers between zero and the average volume per tree in the stand.

Field operation For each tree of the stand the volume will be ocularly estimated. These values must be summed and compared with a random number from the list (every random number is to be used consecutively only one time for one comparison). If the estimated volume is greater than the random number then the volume of the tree must be measured. This can be done by measuring the dbh, the height, and occasionally also an upper diameter. These data should be recorded as well as the tree species and the estimated volume.

The stand volume is finally calculated by multiplying the sum of ocular estimations with the average ratios between measured tree volume and ocular estimated tree volume. The confidence interval of the stand volume is equal to the one calculated from the ratios. The principle of 3P sampling assumes that these ratios between measured and estimated volumes are constant over the range of trees sampled. In a similar way to the number of trees in complete enumeration the sum of ocular estimates is affected by a certain confidence interval from $\pm 2\%$ to $\pm 3\%$.

Complete enumeration using ocular volume estimation of each tree gives accurate results for the total stand volume and for the number of trees by counting the used random numbers; the precision depends on the quality of the ocular estimates and on the number of trees with measured volume. This technique gives only fair information on texture (derived from measured trees) and no information on structure. This technique is faster than complete enumeration but the time taken also depends on the number of the trees in the stand. Considerable experience and knowledge of the stands being sampled is needed.

Sampling Techniques

The following sampling techniques are applied in stand inventories:

- point sampling
- rectangular, quadratic, or circular plots
- *n* tree sampling (point-to-tree distance method)
- tree-to-tree distance method.

Common Problems of All Sampling Techniques Used in Stand Inventories

Correction of finiteness A stand has a defined area. To calculate the correct standard error from a sample a correction of finiteness is necessary. This finite population correction multiplier is generally the square root of 1 minus the quotient of investigation (sampling fraction). This quotient can be calculated as cruised area divided by the stand area (recommended for rectangular, quadratic, or circular plots, *n* tree sampling (point-to-tree distance method), tree-to-tree distance method); or as measured number of trees divided by total number of trees in the stand (recommended for rectangular, quadratic, or circular plots, *n* tree sampling (point-to-tree distance method); or as measured cross-sectional area divided by the stand basal area (recommended for point sampling).

The sample size formula for sampling without replacement from finite populations will differ from the formula for infinite populations

$$n = \left(\frac{t\mathrm{CV}}{A}\right)^2$$

for infinite population

$$n = \frac{1}{\left(\frac{A}{t\mathrm{CV}}\right)^2 + \frac{1}{N}}$$

for finite population where CV is the coefficient of variation in percent, A is the allowable error expressed as a percent of the mean, Student's-t (2-tailed) has $n-1$ degrees of freedom, N is the number of sampling units in the population (e.g., number of trees in the stand), and n is the number of required samples in the stand.

Edge effect bias or boundary overlap In stand inventories sample plots or points can lie near or at the stand boundary. These samples will not be wholly in the stand. This problem, commonly referred as edge-effect bias or boundary overlap, can introduce a bias. In forest inventory with temporary plots this boundary-overlap problem is often solved by moving the plot until the entire plot lies within a stand. This method is not suitable for forest inventory with permanent plots (new boundaries can arise) and for stand inventories because the trees near the edge can be different to the trees in the remainder of the stand, and the trees in the edge zone may be undersampled.

One method of dealing with the edge-effect bias problem is to apply the mirage technique in the field. Another possibility is a computational correction. When the plot center falls near a stand boundary the surveyor measures the distance from plot center to the boundary. If the computational correction is to be applied then this distance is tallied. Otherwise a correction-plot center is established by going this distance beyond the boundary. All trees in the overlap between the two plots are recorded twice. This simple method can be used for circular plots and for point samples (**Figure 1**).

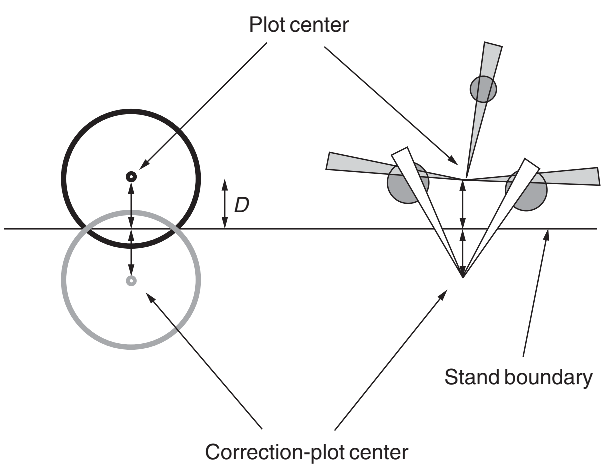

Figure 1 The mirage method for correction of boundary overlap bias when circular plots (right side) or point samples (left side) are used. Trees falling in the control plot are tallied twice.

Computational correction If we define $x = \frac{D}{R}$ with D the distance between the plot center and the stand boundary, and R the radius of the circular plot respectively

$$R = \frac{\text{dbh} \times 50}{\sqrt{\text{BAF}}}$$

in point samples where BAF is the basal area factor and dbh the diameter at breast height in meters. The correction factor can be calculated for the whole plot respectively for each single tree in point samples (but only for trees with R greater than D) with one of the following formulas (arccos gives results in radians, $\cos^{-1}$ gives results in degrees):

$$bf = \frac{1}{\left(1 - \frac{\arccos(x)}{\pi} + \frac{x}{\pi}\sqrt{1-x^2}\right)}$$

$$bf = \frac{1}{\left(1 - \frac{\cos^{-1}(x)}{180} + \frac{x}{\pi}\sqrt{1-x^2}\right)}$$

If a plot falls near to two edges then move the plot along the nearest boundary until the problem is reduced to a one edge effect (**Figure 2**). In very small stands or fractal stand boundaries a complete enumeration is recommended.

Sampling size versus plot size Small sample plots usually exhibit more variability; the coefficient of variation is greater than in large plots. In the literature often the formula suggested by Freese is cited:

$$CV_2 = CV_1 \left(\frac{P_1}{P_2}\right)^{\frac{1}{4}}$$

where CV_2 is the estimated coefficient of variation for the new plot size, CV_1 is the known coefficient of variation for plots of previous size, P_1 is the previous plot size and P_2 is the new plot size.

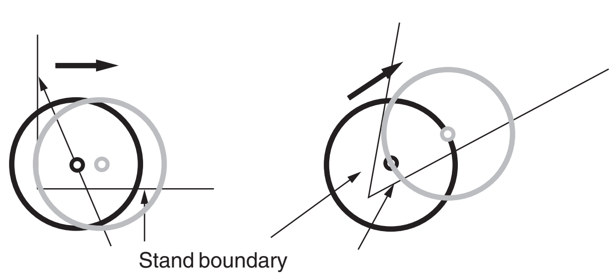

Figure 2 Multiple boundaries overlap: moving the plots along the nearest stand boundary to reduce the problem to a one-boundary overlap.

This formula is a very fair approximation in forest inventories and wrong in stand inventories. In a stand this relation depends on the stand structure. The theoretical correct formula for stands with spatially random distributed trees is:

$$\mathrm{CV}_2 = \mathrm{CV}_1 \left(\frac{P_1}{P_2}\right)^{\frac{1}{2}}$$

The simulation of artificial stands with structure ranging from a quadratic distribution (Clark and Evans index = 2), random distribution (Clark and Evans index = 1), and clumped distribution (Clark and Evans index = 0.5), with different densities (from 400 to 2500 trees per hectare in steps of 300 trees per hectare), and different plot sizes ranging from $12.5\,\mathrm{m}^2$ to $800\,\mathrm{m}^2$ (doubling space) gave the following results:

In uniform stands the calculated exponent is 0.8 with a range from 0.78 to 0.85; in the stands with a random distribution of the trees the exponent is 0.5 with a range from 0.48 to 0.52; and in the stands with a clumped tree distribution the exponent is 0.52 with a range from 0.50 to 0.54. In stands with a clumped tree distribution the effect of enlarging the plot size is slightly more efficient than increasing the sample size. In so-called 'Poisson' forests (random distribution of the trees) there is no difference in the efficiency. But changing the plot size in uniform stands (e.g., plantations) can be very efficient. In uniform populations the coefficient of variation is very small, therefore the influence of different plot sizes in forest inventory is very small, but in a given stand this effect is very high. In one reported study the exponent was calculated to be 0.43 using nine out of 10 stands. Only for one stand was the exponent 0.22 (close to 1/4). This stand was described as including gaps larger than the maximal plot size.

A 'loss of effectiveness' also occurs if spatial correlation exists in the stand , or if the stand can be stratified. In these cases the approximation of Freese is also wrong but can be useful.

Temporary versus permanent plots In stand inventories permanent plots are only useful for investigating special problems or for accurate growth information. Usually temporary plots are sufficient to obtain the required data and results. The major argument against permanent plots in stand inventories is the change in stand boundaries over time, and due to stand dynamics the change of variables of interest (e.g., in a regeneration period browsing is of interest, or several years later precommercial thinning could be important; the variables to investigate will not be the same).

Slope compensation This problem is common to all sampling techniques on steep terrain. Special care must be exercised. There are three possibilities to avoid bias:

1. Compensation by the surveyors. For distance measurement this could be provided by holding the tape more or less horizontal (the maximum remaining slope must be less than 6° or 10%). For point sampling using a stick gauge or a wedge prism, one of the surveyors measures the dbh with a calliper and moves this calliper into the horizontal. The limiting factors are the slope and the plot size. The maximum compensation difference is dependent on the height of the surveyors, somewhere between 2 and 3 meters (taking into account the 6° or 10% mentioned above).
2. Compensation by the measurement instrument used: slope compensation is automatically provided by the Spiegel (mirror) relascope in point sampling. Distance measuring instruments based on laser or ultrasonic technologies can often also measure the slope angle and calculate the horizontal distance.
3. Computational correction of the slope: this can be done either in the field or a posteriori in the analysis. For the latter, the slope angle must be measured and recorded in the field. For field correction a new radius (circular plots) must be calculated:

$$R_{\mathrm{new}} = \frac{R}{\sqrt{\cos(\alpha)}}$$

where R is the intended radius of the circular plot (valid only in flat terrain), and α is the slope angle. The plot will be established holding the tape parallel to the ground. Respectively the new BAF (basal area factor) in point sampling must be calculated as

$$\mathrm{BAF}_{\mathrm{new}} = \frac{\mathrm{BAF}}{\cos(\alpha)}$$

and as field correction this must be applied on the stick length with multiplying the length with $\frac{1}{\sqrt{\cos(\alpha)}}$. For computational compensation the plot size must be calculated as $R^2.\pi.\cos(\alpha)$ and the BAF must be corrected according to the above-mentioned formula. Note that if these computational compensations are used, the means and standard deviations must be weighted to obtain statistically sound results.

Special problems with some sampling techniques

***n* tree sampling (point-to-tree distance method)** This technique is known as *n* tree sampling. One of the advantages of this method consists in the fixed number of trees to be measured per plot, and therefore a more or less clearly defined amount of time taken on each plot. The efficiency of this method decreases when the number of measured trees increases. The surveyed area to find the tree number *n* follows a quadratic function.

Using this technique all means must be calculated by weighting with the area, and the standard deviation can only be approximated by the error propagation law (first term of the Taylor-algorithm – without correlation).

Tree-to-tree distance method In recent years, caused by an emphasis on continuous-cover forests, a very old technique suggested in the nineteenth century has unfortunately had a second revival (the first was in 1940–1960). This sampling method is known as tree-distance technique. The density (number of trees) is estimated from the distances to the nearest neighbor tree. Different proposals deal with the distance to the next, the second or the mean distance between the second and the third nearest neighbor tree. In all these cases a correction factor is reported (e.g., using the distance to the second nearest neighbor tree this correction factor is 0.78 to 0.85 according to different authors).

For the simplest possibility, distance to the next neighbor tree, the correction factor is as follows. Transforming the formula of Clark and Evans (describing the spatial distribution of the trees in a stand),

$$\mathrm{CE} = \frac{2.\bar{e}}{\sqrt{\frac{10000}{N}}}$$

where $\bar{e}$ is the average distance from a tree to its nearest neighbor tree, and N is the number of trees per hectare, will result in the following formula:

$$N = \frac{10000}{\bar{e}^2}\left(\frac{\mathrm{CE}}{2}\right)^2$$

The distance between neighbor trees is dependent on the spatial distribution of the trees in the stand (stand structure); therefore without information on the stand structure the number of trees per hectare (density) can never be derived from tree-to-tree distance information.

Looking Forward

In the future a new technology, airborne laser scanning, could bring a revolution in stand inventories. The first investigations and reports indicate a high performance in the development of digital elevation models but also of digital canopy elevation models. The precision of derived tree or stand height is higher than in terrestrial measurements. Stand and single-tree delineation approaches promise good results under certain (simple) conditions.

See also: **Experimental Methods and Analysis**: Biometric Research; Statistical Methods (Mathematics and Computers). **Landscape and Planning**: Spatial Information. **Mensuration**: Forest Measurements; Growth and Yield; Timber and Tree Measurements. **Resource Assessment**: GIS and Remote Sensing.

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