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Forest inventory by compartments using satellite imagery

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TIIVISTELMÄ: SATELLIITTIKUVIA HYVÄKSIKÄYTTÄVÄ METSÄN INVENTOINTI- JA SEURANTAMENETELMÄ

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A method for using satellite data in forest inventories and updating is described and tested. The stand characteristics estimated by the method showed high correlation with the same characteristics measured in the field. The correlation coefficients for volume, age and mean height were about 0.85. It seems that the method is applicable to practical forestry. Extensive work in programming, however, is required.

Satelliittikuvia hyväksikäyttävä metsän inventointi- ja seurantamenetelmä on esitetty ja testattu. Kuvioittain estimoitujen ja maastossa mitattujen metsikkötunnusten väliset korrelaatiokertoimet olivat noin 0.85 tilavuudelle, iälle ja keskipituudelle. Menetelmä kelvannee käytännön sovellutuksiin. Ponnistukset on suunnattava tehokkaan ja joustavan ohjelmistopaketin luomiseen.

Keywords: Landsat 5 TM, forest inventory and monitoring, two phase sampling, ancillary information
ODC 585+524.6

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1. Introduction

Forest management planning usually requires that the forest area is mapped into compartments of economic size and sufficient homogeneity. It also requires that the necessary data are available for each compartment. The kind of data and their accuracy and the method of data acquisition is determined in relation to the planning situation.

The size of a forest compartment in the southern part of Finland is usually between one and three hectares. The compartment-wise characteristics, such as volume and tree species, change from year to year through growth and removals. Neither are the boundaries of compartments permanent. The state of compartments should be checked periodically. The most common way of updating has been the repetition of compartmentwise mapping and inventory every 10–15 years by help of aerial photo interpretation and ocular field estimation. It has been suggested in many papers that updating would be made more efficient by the registration of cuttings and other forest actions and by the use of growth models.

Satellite techniques clearly offer an additional alternative for compartmentwise inventories as well as for up-dating purposes. This is because the spectral values of individual pixels of satellite imagery and the values of corresponding forest characteristics are often in a clear correlation with each other. The usability of satellite pictures increases with the increase of the correlation. Another fact worth noticing is that one satellite picture covers a large area (180 km × 180 km, Landsat) and the imagery can be repeated many times a year depending, however, on weather conditions.

There are two acknowledged groups of methods applicable to the classification of the earth's surface by help of satellite imagery. They are supervised and unsupervised classification (e.g. Lillesand and Kiefer 1979). Unfortunately, the terminology and classification of these methods may not be apt for forest inventories in the conditions of Nordic countries. The number of combinations of different stand characteristic-values is usually so high that their predefinition for "supervised classification" is not expedient or even possible (cf. Cunia 1978). The final classification of forest characteristics is more appropriately based on field measurements. Satellite imagery is used to make field measurements more efficient by stratification.

The objective of this paper is to present an appropiate way of using satellite data in forest inventories, and especially to compartmentwise forest inventories in the average conditions of Nordic countries. More specifically, an inventory method based on an application of two-phase sampling is described and tested in relatively small scale study conditions. One aim in developing the method is to demonstrate that the use of satellite imagery is in good coordination and concordance with other respective aids, for example with aerial photographs, old map- and inventory information and data from registration, growth functions and permanent sample plots.

The present study is continuation of earlier work. The Finnish studies referred to in this connection are Kuusela and Poso (1970, 1975), Saukkola (1982), Saukkola and Jaakkola (1983), Häme (1984) and Poso, Häme and Paananen (1984).

This study is a continuation to the earlier published 1984 in Silva Fennica Vol. 18 (3). The work was made primarily in the department of forest mensuration and management of the University of Helsinki. The Technical Research Center preprocessed the imagery, both Landsat 3, MSS, and Landsat 5, TM material.

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From the authors Simo Poso was the coordinator and he also wrote the manuscript. Raito Paananen worked for the project in the beginning and calculated results based on Landsat 3 material. Markku Similä continued programming and calculating for Landsat 5 TM material. Thus, he is responsible for the major part of computer work. His input is essential also in the final revision.

2. Description of the design

The background to the design presented here is largely the studies made on the use of aerial photographs for forest inventory purposes in Finland (e.g. Poso and Kujala 1971, 1978 Poso 1972). The method is a modification of two phase or double sampling. The scheme of events is shown in Figure 1.

Maps are needed for defining the inventory area and the set of first phase sample plots. The maps should be supplied with the geographic coordinate values. Both the borderlines of the inventory area and the sample plots are defined by coordinate values.

The technique for delineating the forest compartments directly by satellite data is still not well enough developed. So far aerial photographs are used for the purpose. The borderlines of the compartments are digitized according to the same coordinate system as the first phase sample plots and the boundaries of the whole inventory area.

The primary set of data for the first phase sample plots are obtained from the satellite imagery. For this purpose, each satellite pixel falling to the inventory area is reserved by coordinate values of the same system as used for the compartment boundaries. The pixel or a set of pixels which is closest to a first phase sample plot can now be defined on the basis of coordinate values. The data can then be computed from the closest pixel or the closest set of pixels for each first phase sample plot. Thus, each plot receives a vector of radiation values, each item referring to a specific channel. The system also allows us to define those pixels which occur on boundaries between different compartments. These pixels can be then eliminated or manipulated as desired.

The first phase sample plots are then stratified on the basis of the radiation values and "additional data" from other data sources such as maps and aerial photographs. Where radiation has been measured through many channels (seven channels in Landsat 5, TM) the effective stratification on the basis of radiation values may be problematic. Hence, the application of a principal component procedure seems to be recommendable.

Once the first phase sample units have been stratified each plot can be addressed to a specific stratum. The ground truth for each

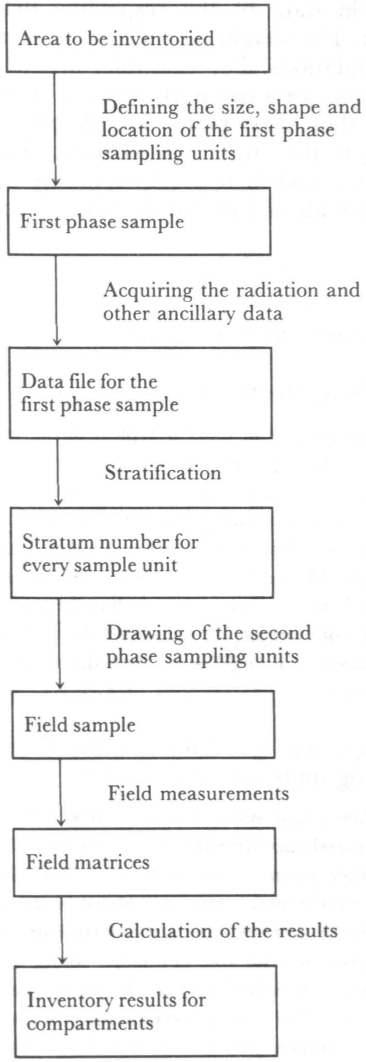

Figure 1. Flow chart of the method.

plot is to be estimated through field measurements. A sufficient number of plots is drawn from each stratum for field measurements. The field measurements are made in a way that makes it possible to calculate stand characteristics for each plot.

The field plots belonging to a specific stratum form a field data matrix. That way each stratum h obtains a field matrix of n(h) field plots. For calculation of final results each first phase sample plot is supplied with the field data of the respective field data matrix. The weight of 1/n(h) is to be applied in calculations. For example, in calculating the results for a compartment one should first define those first phase sample plots which belong to the target comparment. Then distributions and their parameters can be calculated for all of the stand characteristics desired.

Description of the working steps

a. Defining the first phase sample

A large number of units is typical of the first phase sampling. The center points of the units are expressed by geographic coordinates. A systematic equidistant spacing of the units is usually preferable. The size and form of the units are adjusted according to the data sources (see next step!). The center points of the corresponding units of different phases must coincide but the sizes may be different. For example, the radiation values are usually to be measured from larger areas than the respective field characteristics.

b. Acquiring the data for the first phase sampling units for stratification

The first phase data may be usable if they are in distinct correlation with the data measured in the field and if they do not cost too much. Most important possible data sources were listed above in the introduction. Satellite pictures have some outstanding qualities which make them suitable as a major source of the first phase data. The radiation values for an unit center may be obtained from one or several neighbouring pixels depending on how well the centers of the unit and the nearest pixel coincide with each other. The number of radiation values per unit is defined by the number of wavelength channels applied and the number of multitemporal pictures.

Additional data from maps can offer information about land use classes and soil quality and, in the case of old forest maps, other forest stand characteristics as well. Old inventory data transferable to the present situation may be either compartmentwise or plotwise. Data from aerial photographs may also be added to the first phase sampling units.

The minimum size of the first phase sampling unit varies according to the data source. It is a pixel size for satellite pictures, and it is a dot or point representing some area class when data is transferred from a map.

c. Stratification

All of the first phase sampling units are to be stratified on the basis of all of the first phase data. The objective is to make the strata as homogeneous as possible with respect to those characteristics which are regarded as most important in the inventory. This means that those first phase data which best correlate with most important inventory characteristics should have the greatest weight in the stratification. A special consideration to the number and size of the strata should be given.

d. Field measurements

The inventory results can be calculated only for those characteristics measured in the field. At least one sampling unit should be measured in the field for every stratum and all important characteristics should be measured. Measurement of more than just one sampling unit per stratum is preferable for precision calculations and also for practical reasons. The field sampling units have same center points as those used in the first phase sampling. The unit can be, for example, a circular plot, relascope plot or a cluster of plots.

e. Calculation of the results for a given area

The results are computed for a specific area. The area may be a forest stand or compartment or a large geographic region. After the area is defined the first phase sampling units belonging to the area can also be defined.

Every first phase sampling unit belongs to a stratum. The field description for every first phase sampling unit is obtained by the field measurements of the respective stratum. Accordingly, every first phase sampling unit belonging to the given area has field measured values and hence it is possible to calculate results for any set of first phase sampling units and also for a given area.

3. Experimentation with the method

3.1. General outline

The first experiments with the method were based on Landsat 3 material and six study areas in South Finland. The field measurements consisted of relascope plots measured in 1980–81 with BAF 2. The material and the results have been described by Poso, Häme and Paananen (1984). Later in 1983 and 1984 material was collected according to equal outlines in Hyytiälä, the forest station of the University of Helsinki (Figure 2). The main content of the material is given in Table 1.

Material 1 consisted of six separate study areas ranging from 7.8 to 50 hectares in size (Poso et al. 1984). Field material of Materials 2, 3 and 5 was gathered in Hyytiälä within an area of some 200 hectares and that of Material 4 within and area of some four sq.km.

An effort was made to ensure that the field plot centers and the centers of the first phase sample units corresponded accurately. Differences in the sizes of the units, however, were acceptable. The situation in respect of some characteristics is given in Table 2.

Radiation values for a plot were taken from between one and four nearest pixels. The sizes for treatment class and site were larger than for stand volume and age because the estimations in the former case were also based on plot surroundings.

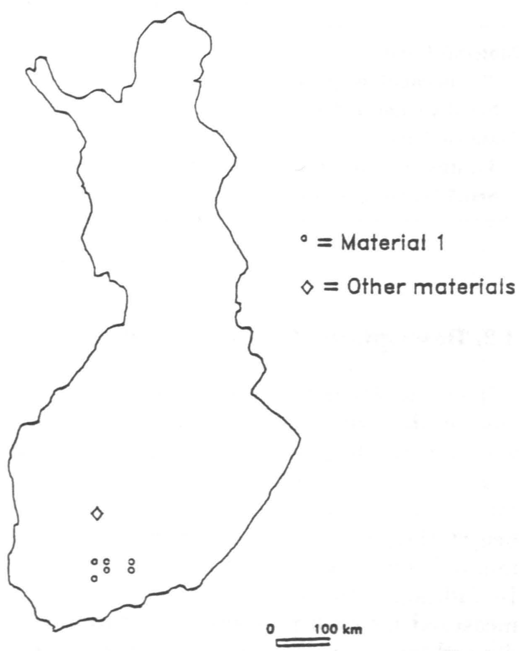

Figure 2. Location of the study areas.

The discrepancy in the size of units for separate observations is not necessarily harmful. It is probably sensible in this case that the units for stratification are larger than those economical for field measurements.

Table 1. Description of the main study materials.

	Material				
	1	2	3	4	5
Imagery	Landsat 3 MSS		Landsat 5 TM		
Date	June 10,80	Aug 12,82	September 15,84		June 21,85
Channels*	4	4	6	6	6
Pixel size	79 m × 79 m		30 m × 30 m		
Field plots	602	682	1472	76	1472
Plots/ha	4	4	8	not relev	8
Year of field work	1980–1981	1983	1983–1984	1985	1983×1984

* The channels of Landsat material used were as follows:
MSS bands: 500–600, 600–700, 700–800 and 800–1100 nm
TM bands: 450–520, 520–600, 630–690, 760–900, 1550–1750 and 2080–2350 nm

Table 2. Examples of sizes of first and second phase sample units.

	Size of measurement, hectares Radiation value	Field measurem.
Material 1 and 2		
Treatment class and site	1.3	0.1
Stand volume and age	1.3	0.03
Material 3 and 5		
Treatment class and site	0.24	0.1
Stand volume and age	0.24	0.03

3.2. Description of the field material

The unit for measurement of the growing stock in three first materials and in Material 5 was a variable plot or relascope plot with basal area factor, BAF, of two. This means, for example, that a tree with 20 cm of breast height diameter is to be measured at a maximum distance of 7.07 m from the plot center. In addition to the tree tally, mean height was measured for each plot and the volume was derived by using the volume tables by Nyyssönen (1954). In some cases, the basal area measured for a plot was adjusted ocularly to improve the representation of the immediate surroundings of the plot.

The plot measurements produced the following stand variables:

1. site class (codes 0–4)
2. development class (codes 0–4)
3. age (years)
4. proportion of pine (0–10)
5. " " spruce (0–10)
6. " " deciduous trees (0–10)
7. volume (cubic metres per hectare)

The plots for Materials 1 and 2 were marked equidistantly on 1:10 000 black and white aerial photograps to represent 50 m × 50 m in the field. Those plots of Material 2 falling on the distinct stand borderlines were moved 10–20 metres further along the coordinate lines until the plots were totally in one stand only. The location of each plot was marked with poles and geographic coordinates with 10 m accuracy.

The field sampling of Material 2 was intensified to Material 3. The plots were measured at the same pattern of 50 m × 50 m but the plots fell in the middle of the squares defined by the plots of the Material 2 as corners. That way the density of field material was 8 plots per a hectare.

The field data for 1983 were updated to the 1984 level by applying growth models by Nyyssönen and Mielikäinen (1978).

Field data of Material 4 were those measured in the square or rectangular stand plots in Hyytiälä. The average size of plots varied from 0.08 to 0.24 hectares. The average size was 0.14 hectares and the average volume of the plots 166 cu.m. per hectare.

The forest areas of Materials 2, 3 and 5 are dominated by the tree species pine and spruce, as shown in Figure 3. Deciduous trees are the main tree species only on 5.5 % of the area and mostly in young stands. The mean volume of deciduous trees sample plots is 17 m^3/ha. The proportion of spruce increases with the age of the stands. There are two peaks in the distributions of age and volume. The first one is at about 20 years and 25 m^3/ha. The second one is at about 90 years and 200 m^3/ha. The mean volumes for pine and spruce sample plots are 59 m^3/ha and 100 m^3/ha, respectively. As a whole the forest area can be regarded as rather homogeneous.

3.3 Plotwise radiation data

Two major alternatives were considered when making choice of sampling unit. First, the natural unit to be dealed with seemed to be the pixel. This alternative, however, resulted in some difficulties in measuring and calculating field data for a unit. After experimentation with various units with Material 1 it was decided that a more preferable choice for a unit is a sample plot, the location of which is to be defined by map coordinates. The latter alternative means that the field estimates may be based on the measurements of one sample plot alone but for radiation values it may be better to use more than only the nearest pixel.

The vector of radiation values of separate channels was calculated for a plot on the basis of from one to four pixels nearest to the plot. A weighting procedure dependent on distance of a pixel from plot center was applied to determine the average radiation value for a plot in Materials 1 and 2 (see Poso et al. 1984), whereas arithmetic means were applied to Material 3, 4 and 5.

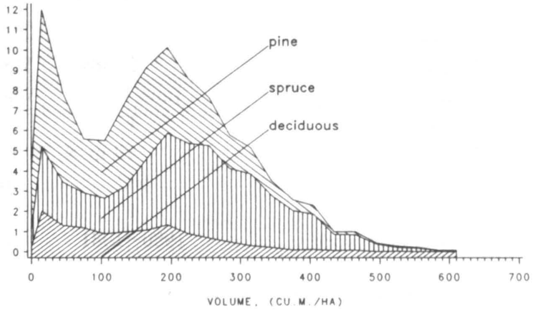

Figure 3. Distribution of volume by tree species.

3.4. Delineation data

The forests of the study area were delineated to management compartments by photo interpretation and field work. The borderlines of the compartments were digitized and transferred to Finnish uniform coordinate system, i.e. to the same coordination applied in the location of satellite pixels. The borderlines were classified into two classes:

1. those separating two distinctly different compartments, for example open area and mature forest;
2. those borderlines separating compartments which were not sufficiently different from each other.

The purpose of the classification of the borderlines was to be able to treat those pixels and plots which fell close to the borderlines in a specific way.

3.5. Map data

Those classes identifiable from the general maps and regarded as useful for forest management purposes were digitized by using special map data program system called NALLE in the Finnish Forest Research Institute. These classes were mineral soils, peatlands, agricultural lands, roads, waters, graval pits, power lines etc. The classification data were added to other first phase sample plot data where they were easily usable for stratification.

3.6. Photo interpretation

Delineation of compartments was first made on 1:10 000 aerial photographs by photo interpretation. In connection with delineation, it was easy to see those compartments which were treeless or which were young plantations. These compartments were marked by a special code which was added to the records of the plots belonging to the respective compartments. The data could then be used for stratification of the sample plots.

4. Stratification

4.1. General outline

The ultimate objective of stratification is to arrange the first phase units into homogeneous groups of strata with regard to all of those forest stand characteristics which are important for forest planning or subject to a specific forest inventory. A good stratification presupposes a high correlation between radiation values from satellite imagery and forest stand characteristics as measured in the field as well as a high level of homogeneity of strata with regard to the radiation values. If the both conditions are fulfilled, the strata are also fairly homogeneous with regard to stand characteristics as measured in the field. The effect of stratification can be estimated by the formula

(1) $P_w = \sum_{j}^{K} \sum_{h}^{L} (W_h \cdot S_{jh}^2 / S_j^2)$

where

P_w = proportion of within strata variance from the total variance

L = the number of strata

W_h = the proportion estimate of stratum h

K = the number of forest stand characteristics to be estimated

S_{jh}^2 = the variance of forest stand characteristic j in a stratum h

S_j^2 = the variance of forest stand characteristic j without stratification (= total variance)

The formula gives similar weight for every stand characteristic. The smaller the proportion is the more efficient is the stratification. The proportions can be estimated for each stand characteristic separately and each proportion can be supplied by a different weight for the final conclusion regarding to the total efficiency of stratification. This is because all of the stand characteristics may not be regarded to be of equal value.

The number of strata was based on empirical experiments and a theoretical guidance by Cochran (1977). He considers the problem under the assumptions that samples in each stratum are of equal size and that the dependence of the estimated stand variate on the stratifying factor is linear. Using the simple regression model Cochran shows that the useful number of strata increases with increasing correlation coefficient, but only very little reduction in variance is to be expected after some ten strata, even if the correlation coefficient would be very high. From a practial point of view it is evident that also other factors affect the useful number of strata. These are, for example, the extent of inventory area and the number of items in the first phase data vector (e.g. number of radiance values and data from maps).

4.2 Designing of the stratification

The number of strata was first fixed at fifteen in all of the experiments. In the light of the remarks above and earlier experiments (Poso et al. 1984), this was seen as sufficient or even higher than necessary with respect to spectral values of satellite imagery, and somewhat too low for cases where information from maps and aerial photographs were also utilized for the stratification. Fixing the number of strata means some simplification, which should be noted when drawing conclusions.

Stratification is the central factor when considering the overall quality of the inventory. Stratification can be based on a large number of different data. The alternatives to using separate data for the stratification in the experimentation of this study are as follows (cf. Table 3 for more details):

Table 3. The elements for building alternative experiments for stratification (some items have been explained more thoroughly in the text).

Procedure	Description
1	Stratification based on spectral values of all of the plots and pixels close to the plots
2	As Proc. 1 but restricted to a subpopulation forest land, i.e., nonforest land has been eliminated on the basis of map information.
3	Pixels, which fall close to compartment boundaries of distinct nature have been neglected in the calculation of the spectral values for the first phase sample plots.
4	Masks from maps have been used to differentiate peatland from mineral soils and forest land from other land use classes such as roads and agricultural land.
5	Forest land has been stratified by photo interpretation into two strata: i) treeless or young plantations and ii) older forests.
6	Principal components for stratification are calculated from the correlation matrix
7	Principal components for stratification are calculated from the covariance matrix
8	Outliers have been treated separately in the stratification on the basis of the two first principal components.
9	Sample plots falling close to compartment boundaries have been neglected in the calculation of compartmentwise inventory results.

- spectral values of plots alone
- spectral values and map information
- spectral values, map information and information from photo interpretation

Stratification based on spectral values was made using the principal component technique. This offers a means to intensify the information given by a large number of separate spectral channels, the spectral values of which are often correlated strongly with each other. According to Table 4, the three first principal components include 93–98 % of the information of the six Landsat 5 TM channels.

The basis for calculating the principal components can be a correlation or a covariance matrix. According to Singh and Harrison (1985) both alternatives have given good results. Using of covariance matrix means that those channels which show largest variation in spectral values obtain the highest weights in the stratification. In the case of the correlation matrix, the distribution of each channel values is standardized and thereby the separate channels obtain equal weights in the stratification. The three first principal components for Material 3 are given in Table 4.

According to Table 4, the eigenvector values for the first principal component from the correlation matrix are close to each other whereas the coefficients in the first eigenvector values (PC1) from the covariance matrix are often far from each other. The standard deviations of spectral values of channels 1, 2, 3, 4, 5 and 7 are 1.5, 1.2, 1.6, 5.3, 7.2, and 2.6 respectively. The highest coefficients of PC1 from covariance matrix in Table 4 refer to the channels with highest standard deviations.

The sample plots were stratified by computer programs BMDPKM (see BMDP Statistical Software 1981) for Material 1 and 2 and by SAS Fastclus procedure (SAS 1982) for Material 3. In these clustering programs the importance of the principal component depends on the variance which this principal component accounts (see also 5.3). Because these clustering programs follow minimum variance criterion it is often regarded as an advantage that stratifying factors, three principal components, are uncorrelated. For outliers, i.e. plots which differed drastically from the others in regard to the first two principal components, the following procedure was applied. First the cases were removed and the stratification was made with the rest of the plots. The residual cases were then included in the strata closest to them (Table 3, Proc. 8).

Table 4. Magnitude of eigenvectors for spectral values from Landsat 5 TM material with 1401 sample plots.

	Correlation matrix			Covariance matrix		
Channel	PC1	PC2	PC3	PC1	PC2	PC3
1	0.351	0.911	0.166	0.112	–0.031	0.866
2	0.415	0.182	0.234	0.113	0.028	0.176
3	0.426	–0.004	–0.171	0.160	–0.043	0.365
4	0.395	–0.313	0.709	0.528	0.842	–0.054
5	0.433	–0.158	–0.310	0.776	–0.489	–0.241
7	0.424	–0.118	–0.539	0.261	–0.221	0.155
	Cumulative percentages					
	79.9	87.9	93.2	88.4	96.8	98.3

5. Results

5.1. Accuracy in data location

The basis for the location of field plots was a map and the uniform coordinate grid on that as described in Sections 3.2 and 3.3. The estimated accuracy of locating plots in the field was 10 m in relation to the dot on aerial photograph.

The location of the satellite image was carried out primarily in the Technical Research Centre of Finland. The procedure for locating the satellite image for material 1 was based on the Versatec grey level map for MSS 5 (cf. Poso et al. 1984). In the case of material 2 Versatec grey level map (MSS 7, 0.8–1.1 micrometers) was printed out from a rather small area (about 4000 hectares). Then 26 control points were identified in the grey level map as for the basic map. Using least squares method, the coefficients of the third degree coordinate transformation polynomial were determined. The standard deviation of errors was 26 m for the control points Material 2.

For Materials 3 and 4 the coefficients of bivariate third degree mapping function were determined as a part of the geometric correlation of the larger area (over 100 km^2). The values of channel 4 (0.76–0.90 micrometers) were monitored. Sixteen control points, usually islands, were located both in rows and columns of the satellite imagery as well as in geographic coordinate system. Then the least squares method was applied to find a formula which transformed the pixel location based on rows and columns to that based on geographic coordinates. The standard deviation of errors in the levelling of the control points was 13 m.

For material 5 the transformation of pixel locations proceeded as in the cases of materials 3 and 4, but the number of control points was 13 and standard deviation of errors 15 m.

The accuracy of location, i.e. the geographic correspondence of plot and pixel materials was further studied indirectly on the basis of coefficients of correlation. The correlation coefficient for plotwise volumes (m^3/ha) and the first principal component values were calculated. By changing the location of pixels systematically in relation to the location of field plots the change in correlation coefficient could be studied. The number of plots was 1472 and two Landsat 5 TM images were used. Results are in Table 5. Presumably the most accurate location provides the highest correlation. This assumption is supported by the fact that in both images there was only one peak among the correlation coefficients. Around that peak correlation coefficients decreased more or less rapidly depending on the direction of change. It is also noteable that the change in both images is almost similar with regard to distance as well as direction (Table 5). This leads to an assumption that the discrepancy in the original location of pixels and field plots originates from the radial distortions characteristic of aerial photographs.

The procedure for stand volume explained above was also applied to other stand characteristics such as age, basal area, and mean height. The results were similar; on average, the improvement of some 0.1 units in correlation coefficients were experimented for Material 3 and 0.05 units for Material 5. The maximum coefficients of correlation were 0.59 with locational change of 25 and 15 m in the separate coordinates for Material 3 (Landsat 5, September 15, 1984) and of 10 and 15 m for Material 5) Landsat 5, June 21, 1985).

When field and satellite data were combined for the later analysis of materials 3,4, and 5, those changes in the location of data sets were used which gave the highest correlations.

5.2. Correlations between plotwise characteristics

The study material allows the calculation of correlation coefficients for plotwise radiation values and stand characteristics measured in the field (Table 6). The assumption of exponential dependance between radiance values and stand characteristics gives slightly better correlation coefficients for the TM material. For the sake of comparison, all re-

Table 5. Sensitivity of the coefficient of correlation between the plot volume and the first principal component value to the location of the satellite imagery. The upper value refers to Landsat 5 Sept. 1984 and lower value to Landsat 5 June 1985.

North – South	Change in coordinate value, in meters East – West –60	–30	–15	0	15	30	60 m
+60	.31 .28			.52 .45			.37 .32
+30		.45 .40		.58 .54		.55 .53	
+15			.49 .52	.54 .57	.57 .60		
0	.27 .26	.38 .41	.43 .49	.49 .57	.52 .58	.51 .56	.43 .44
–15			.39 .47	.43 .53	.45 .53		
–30		.28 .33		.35 .44		.40 .48	
–60	.17 .18			.26 .31			.32 .35
m							

sults in Table 6 are presented without applying any transformation to the data.

Materials 1 and 2 refer to the MSS of Landsat 3. The field material of the former was collected from six separate study areas in southern Finland, whereas the field material of the latter is concentrated in a region of some 1.5 km×0.8 km. The lower correlations of the former material refer to the fact that there were huge variations between the correlation coefficients of the six separate study areas. Reasons for variation may be found in different location accuracies, in differences in spatial homogeneity of stand characteristics as well as in weather conditions.

The comparison of TM material (Material 3) with MSS material (Material 2), the field data of which was collected from the same area, shows a distinct difference in correlation coefficients in favour of the former. The first principal component shows correlation coefficient of –.45 and –.43 for stand volume and age for the case of Landsat 3 MSS material. The corresponding values for Landsat 5 TM material were considerably better, i. e. –.62 and –.62. Only modest correlations were calculated for the proportions of tree species, and no improvement was shown with increased spatial resolution.

Table 6 includes a peculiar feature: the first principal component (PC1) gave the highest correlations with almost all of the measured charcteristics in Material 2, whereas the first principal component was not so good in Material 3.

Comparison of Materials 3 and 4 shows the effect of the size of sample unit on correlation. The plots of Material 4 are square or rectangular, their size varying from 0.08 to 0.20 hectares, whereas Material 3 consists of rather small relascope plots. The sizes of the first and second phase sample units are closer

Table 6. Coefficients of correlation between radiation values and field measured forest stand characteristics.

Material for radiation values (cf. Table 1)	Characteristics measured in the field					
	Volume m³/ha	Age	Proportion of pine	spruce	broad leaves	Site class
(n=602)						
1, MSS 4	–.27	–.42	.21			–.03
1, MSS 5	–.35	–.40	.42			.22
1, MSS 6	–.29	–.45	–.04			–.21
1, MSS 7	–.24	–.44	–.07			–.26
1, PC 1	–.34	–.51	.14			–.10
1, PC 2	–.10	–.03	.43			.36
(n=682)						
2, MSS 4	–.34	–.34	.29	–.36	.03	
2, MSS 5	–.37	–.34	.35	–.42	.05	
2, MSS 6	–.45	–.42	.33	–.50	.27	
2, MSS 7	–.44	–.43	.30	–.48	.31	
2, PC 1	–.45	–.43	.36	–.50	.19	
2, PC 2	.07	.07	.04	.09	–.31	
(n=1403)						
3, CH 1	–.46	–.45	.30	–.35	.04	.16
3, CH 2	–.57	–.56	.34	–.45	.15	.20
3, CH 3	–.56	–.56	.35	–.47	.15	.18
3, CH 4	–.60	–.65	.17	–.34	.25	.03
3, CH 5	–.58	–.58	.34	–.48	.18	.16
3, CH 7	–.55	–.53	.36	–.47	.13	.17
3, CH 6	–.35	–.27	.41	–.43	–.02	–.34
3, PC 1	–.62	–.62	.35	–.48	.17	.17
3, PC 2	.08	.12	.10	.01	–.18	.07
(n=76)						Height
4, CH 1	–.63	–.54	.24	–.22	–.04	–.69
4, CH 2	–.69	–.61	.20	–.28	.08	–.72
4, CH 3	–.64	–.60	.23	–.29	.06	–.71
4, CH 4	–.78	–.77	.06	–.25	.26	–.81
4, CH 5	–.66	–.65	.16	–.24	.11	–.74
4, CH 7	–.64	–.60	.20	–.24	.03	–.72
4, CH 6	–.51	–.50	.22	–.19	–.07	–.59
4, PC 1	–.70	–.66	.20	–.26	.07	–.76
4, PC 2	–.29	–.30	–.17	–.07	.37	–.23

to each other in Material 4 than in Material 3. Another difference is in the location of field plots. The plots of Material 4 are placed subjectively in a typical and often center part of a stand, which leads to smaller boundary problems than in the case of relascope plots. These are the major reasons for distinctly higher correlation coefficients of Material 4 over Material 3 (Table 6).

To study the effect of the imagery date on the correlation coefficient, the coefficients corresponding to those that were included in Table 6 for material 3 (Landsat 5, September 15, 1984), were calculated for material 5 (Landsat 5, June 21, 1985). The correlation coefficients showed a high consistency with respect to the first principal components. For the second principal components there were already some differences which probably originated from seasonal changes of spectral reflectance. According to Swain and Davies (1978) the dominant factors controlling leaf reflectance of green vegetation are leaf pigments for channels 1–3, cell structure for channel 4 and water content for channels 5 and 7.

Also of interest are those channels which correlate best with tree species and in this respect the results for materials 3 and 5 are consistent. Reflective infrared channels 5 and 7 are best for pine and spruce and channel 4 for broad leaved species.

The correlations for various principal component values based on correlation matrix are illustrated in Figure 4. The lines have been drawn only for stand volume and site. The figure shows that most information is gained from the first principal component. However, there are studies using Landsat TM material where higher-order principal components contain valuable information (Townshend 1984). According to the results for Materials 3 and 5 this seems to be true especially for deciduous trees.

5.3. Within strata variances of plotwise stand characteristics

The key working step in a successful application of the inventory method is the stratification. A simplified approach was used here, the number of strata being kept constant, i.e. 15, in all stratification strategies.

The stratification was performed by FASTCLUS clustering program which belongs to SAS program library. The sample plots were partitioned into disjointed clusters in the three dimensional vector space spanned by three first principal components. The measure of similarity between two sample plots was the euclidean distance between plots in this space. FASTCLUS is based on the k-means method and it tries to minimize the sum of squared distances from the cluster means, i.e. it follows the minimum variance criterion. When using FASTCLUS one assumes that all clusters have same hyperspherical shape. FASTCLUS is very sensitive to outliers (SAS 1982) and to small clusters near large ones (Hand 1981).

The side distributions of the three dimensional space of principal component values are shown in Table 7. The range of the values indicates the importance of the principal component in the stratification. Accordingly,

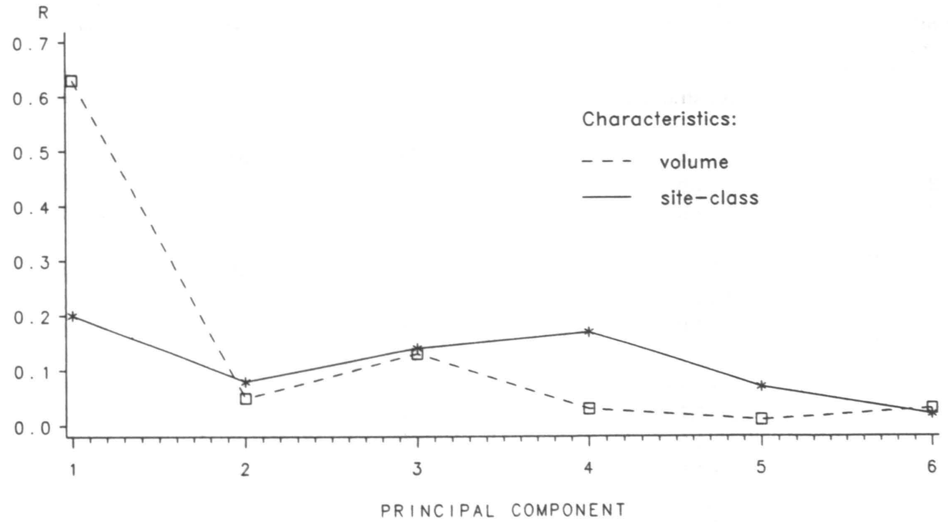

Figure 4. The correlations between PC 1–6 and the stand characteristics, volume, and site class. TM material from September 1984.

Table 7. The distribution of the first three principal component values.

PC	Middle of class −15	−10	−5	0	5	10	15	20	25	30	35	total
1	1.10	19.1	26.3	25.0	12.1	6.2	3.3	3.6	2.6	0.4	0.4	100
2	0.1	1.1	13.5	69.9	14.7	0.7	0	0	0	0	0	100
3	0	0	1.4	95.9	2.7	0	0	0	0	0	0	100

the first principal component has the highest and the third principal component the lowest weight in the stratification.

All stratification strategies share the same feature concerning the distribution of strata according to stratum size. The first 3–4 strata contain the majority (50 %–70 %) of the sample plots, and the last five strata contain about 5 %. This follows from the concentration of the spectral values and the algorithm applied to the stratification.

The basic equation for measuring the success of the stratification was given in Section 4.1 (Equation (1)). The within variances can be calculated separately for each characteristic. The equation presupposes that each stand characteristic j is equally important. If this is not true, weights should be introduced. The within strata variances in relative measures have been collected for alternative stratification strategies and materials in Table 8.

It can be seen from the Table 8 that only modest improvement has been taken place for Material 2 when the ancillary information, i.e. procedure 4, has been added to the list of stratifying factors.

The results with Material 3 are somewhat more promising with respect to the use of ancillary information (procedures 4 and 5). The relative within variance fell from some 0.58 to .51 when both map and photo information was used for stratification in addition to satellite data.

Table 8. Percentages of within strata variances from total variances for some materials, stratifications, and stand characteristics.

Material (cf. Table 1)	Stratification (cf. Table 3)	Volume	Age	Mean height
	No stratification	100	100	100
2	1,6	79	83	81
2	2,6	80	83	81
2	4,6	79	81	78
3	1,7	61	61	56
3	2,3,7	59	57	52
3	2,3,7,8	57	57	49
3	2,3,4,7	59	56	51
3	2,3,4,7,8	59	58	51
3	2,4,5,7	59	57	51
3	2,4,5,7,8	57	56	48
3	2,3,4,5,7	59	56	49
3	2,3,4,5,7,8	57	54	47
3	2,3,4,5,7,9	58	55	47
3	2,3,4,5,7,8,9	56	51	43

The minimum variance criterion which FASTCLUS follows led to a separate treatment for outliers (procedure 8). With one exception this improved results.

The effect of the number of strata on within strata variances is presented in Table 9. It shows that no clear optimum number of strata can be found for the different stratification strategies, as is to be expected according to Cochran (1977). This observation is also in concordance with the experiences which are achieved in the two phase sampling based on aerial photo interpretation (Mattila 1985). When no ancillary data is used (columns a and b), the within strata variances do not decrease importantly after 15 strata. With ancillary data (column c) the appropriate number of strata is higher, about 20 for this area and material. The differences between the results based on the correlation matrix (column a) and covariance matrix (column b) are small, but nevertheless favour the latter.

5.4. Accuracy of compartmentwise forest stand estimates

In order to study the accuracy of compartmentwise estimates the list of results was first calculated for each compartment on the basis of respective plot values (Table 10).

There is a set of factors affecting the accuracy of compartmentwise estimates. The geographic location of digitized borderline data may be erronous, nor are field plots and pixels located without errors. A theoretical demonstration of the effects of these factors is presented below. It is based on an assumption that the standard deviation in locating the borderlines, pixels and plots is 10 m and the form of the compartments is circular. Probability refers to the probability of a pixel or a plot taken randomly to fall to a wrong compartment.

	Size of compartments, hectares 0.5	1.0	1.5	2.0	2.5	3.0
Probability, %	20.0	15.5	13.0	11.5	10.5	9.5

Field plots also include errors in measurements and, because of small size, one plot cannot represent a compartment without a large random variation. This problem can be solved to great extent by increasing the number of field plots. The accuracy of compartmentwise estimates in two stratification strategies are compared in Table 11.

Number 65 in the Table 11 refers to all of the management compartments while number 43 refers to the management compartments of over one hectare. These 43 large compartments cover over 90 % of the forest area. In calculating the results, field matrices have been simplified to mean vectors. The correlation of estimated and field measured characteristics are fairly high for continuous stand characteristics.

Table 9. Plot variances within strata for three stratifications*. Material 3, N=1401 in (a) and (b) and N=1055 in (c).

Number of strata	Volume (a)	(b)	(c)	Age (a)	(b)	(c)	Height (a)	(b)	(c)
1	100	100	100	100	100	100	100	100	100
3	66	64	87	68	67	86	58	60	81
5	61	64	64	64	67	64	55	59	57
10	61	59	60	61	56	56	53	51	46
15	59	59	58	58	57	55	51	52	47
20	58	57	55	58	55	49	50	50	41
25	59	58	54	58	55	49	52	49	41

* a = procedures 2,3,6 (cf. Table 3)
b = procedures 2,3,7
c = procedures 2,3,4,5,7,8,9

Table 10. Results calculated for a compartment: an illustration

Compartment: 15	Number of plots: 31			Area: 4.74 hectares
Characteristic	Satellite est. mean	Field estimate mean	Field estimate std. dev.	Difference of means
Age, years	78.9	95.2	25.5	−16.3
Mean height, m	17.4	20.6	4.6	−3.2
Volume, m^3/ha	192	234	85	−43
Proportion of				
– pine, 1/10	6.0	6.8	2.8	−0.8
– spruce, 1/10	3.5	2.4	2.3	1.1
– broad leaves 1/10	0.5	0.8	0.8	−0.3

Basis for classification	Distribution of plots according to satellite estimation: Code for area class* 0	1	2	3	4	5	6	7	8
Land use class		30					1		
Soil class	1	22	3	5					
Site class	1			11	18	1			
Main tree sp.	1	25	5			1			
Development cl.	1		1	13	15				

* The codes refer to those used at the University of Helsinki. Their actual meaning is here of no practical importance.

Table 11. Coefficients of correlation, r, between estimated and field measured values of the stand characteristics

Characteristic	Stratification (cf. Table 3) 2,3,7,8		2,3,4,5,7,8,9	
	number of compartments 65	43	65	43
Age, years	.85	.90	.87	.90
Height, m	.84	.89	.89	.91
Volume, m^3/ha	.86	.91	.87	.91
– Pine	.76	.80	.62	.60
– Spruce	.84	.91	.80	.87
– Decidious	.39	.45	.48	.52

The table shows a substantial increase in correlation when management compartments under one hectare of size were dropped out. the result is in concordance with expectations. The small compartments have lower numbers of plots than the large ones and a higher proportion of plots fall close to compartment boundaries where there is a high risk for a plot to be located in the wrong compartment. An attempt to reduce this risk was made by neglecting in the calculations those plots which fell closer than 13 m to compartment boundaries (procedure 9). On the other hand, this reduction means that the number of sample plots in the compartment decreases. Secondly, to insure that the spectral values of a sample plot would represent only one compartment, procedure 3 was applied (cf. Table 3). For some small narrow compartments this procedure exhausted the pixels of the compartment.

Adding map and photo data as ancillary information (stratification 2, 3, 4, 5, 7, 8, 9) had a favorable effect on the correlation with the exception of tree species distribution. Understandably, the correlations are higher for the group of compartments the size of which is at least one hectare.

The study of the accuracy of area-class estimation is more problematic than that of continuous stand characteristics. The use of mean vectors made it impossible to give any sensible estimation of the nominal scale characteristics, such as main tree species or soil class. For the ordinal scale characteristics, such as development class (codes from zero to four accepted) or site class, the estimates were not equally haphazard. The coefficient of contingency for four area class characteristics (cf. lower part of Table 10) are shown in the following set up.

	Stratification: Withour ancillary information	With ancillary information
	Coefficient of contingency	
Development class	0.69	0.71
Sites class	0.50	0.52
Soil class	0.22	0.74
Main tree species	0.57	0.58

The ancillary information has improved the correlation only slightly for development class, site class and main tree species. If the development class of a stand is assumed to be continuous with the range 1−4, the respective corresponding correlation coefficients are -83 and .86. The nominal scale characteristic soil class, however, is distinctly improved by map information, which was used to differentiate mineral soil, pine swamps, spruce swamps and treeless peatlands. For a statistically sound estimation of the ordinal or nominal scale variables in connection with this estimation procedure, see Peng (1987).

Compartmentwise stand characteristics estimated by satellite pictures and measured in the field have been compared also in Figures 5, 6 and 7.

5.5. Compartmentwise estimation results of three forest lots

In the autumn 1986 the compartmentwise estimation was extended outside the study area of Hyytiälä to three forest lots using the field measurements from Hyytiälä as the second phase sampling units. The objective was twofold. First, further experiments were needed to achieve a better view concerning the overall accuracy level of the estimation procedure. Secondly, this enabled the testing of the procedure when no sample plots were available from the area to be inventoried.

In all forest lots, systematic 25 m · 25 m sampling was used as the first phase sample. The delineation according to aerial photograph and the digitizing of the delineation were carried out by forestry students who also made the ocular estimation of the lots in the summer 1986 (Härkönen and Itkonen 1986). The lots were not farther than about 20 kilometers from the study area of Hyytiälä. Some statistics concerning the forest lots are presented in the following table.

	Forest lot 1	2	3
Area, ha	195	91	196
Number of compartments	113	72	70
Number of estimated comp.	102	70	68
Number of of second phase sample	1403	191	1403

Procedures 3 and 9 (cf. Table 3) were applied. Those compartments without any pixel or first phase sample plot were not estimated. Hence, the numbers of compartments in the second and third rows in the table above are different. The sizes of neglected compartments were small, usually about 0.2 hectares. When the second phase sample consisted of 1403 units, the same field plots were utilized as for Material 3 (cf. Table 1). On the other hand, the second phase sample of 191 units refers to those relascope plots with BAF 2, which were measured with systematic 100 m · 100 m sampling in the study area of Hyytiälä in the autumn 1986 applying to the same standards as applied to other relascope materials. The imagery was,

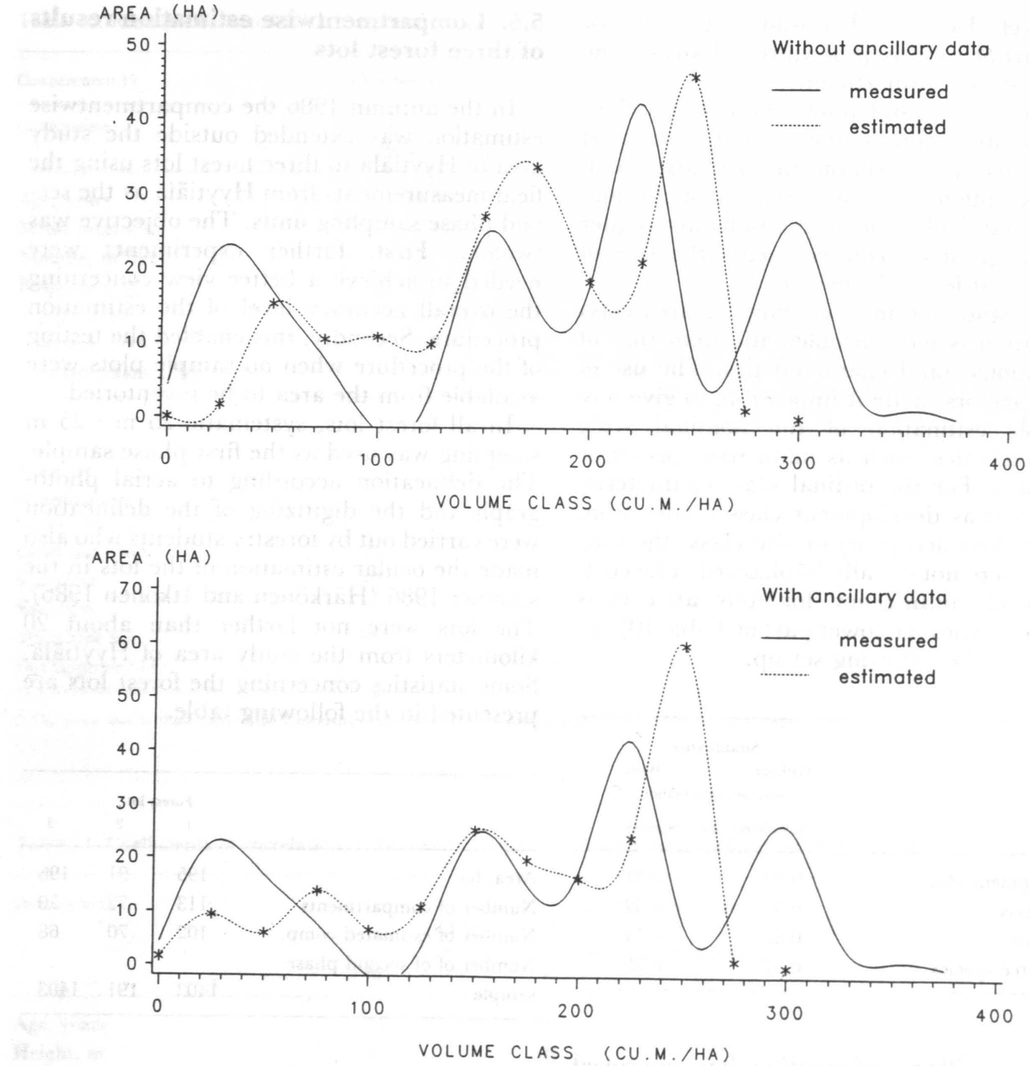

Figure 5. Comparison of satellite estimates and field measured results for compartmentwise volumes when no ancillary information (upper part) and when ancillary data (lower part) was applied to the stratification.

in all three cases, that of Landsat 5 TM taken in June 1985.

The first phase sample consisted of the first phase sample of a forest lot and the Hyytiälä sample plots. This sample was stratified into 25–30 strata depending on whether there was open peatland in the forest lot or not. The estimates obtained by this procedure were compared with those obtained by forestry students with ocular estimation. Figure 8, in which the differences between the satellite estimates and the field measured results can be seen, should be compared with Figure 7.

Measures for the quality of the estimation results were correlation coefficient, r, and root mean square deviation divided by the arithmetic mean of the measured characteristic, denoted here by c. The formula for c is as follows:

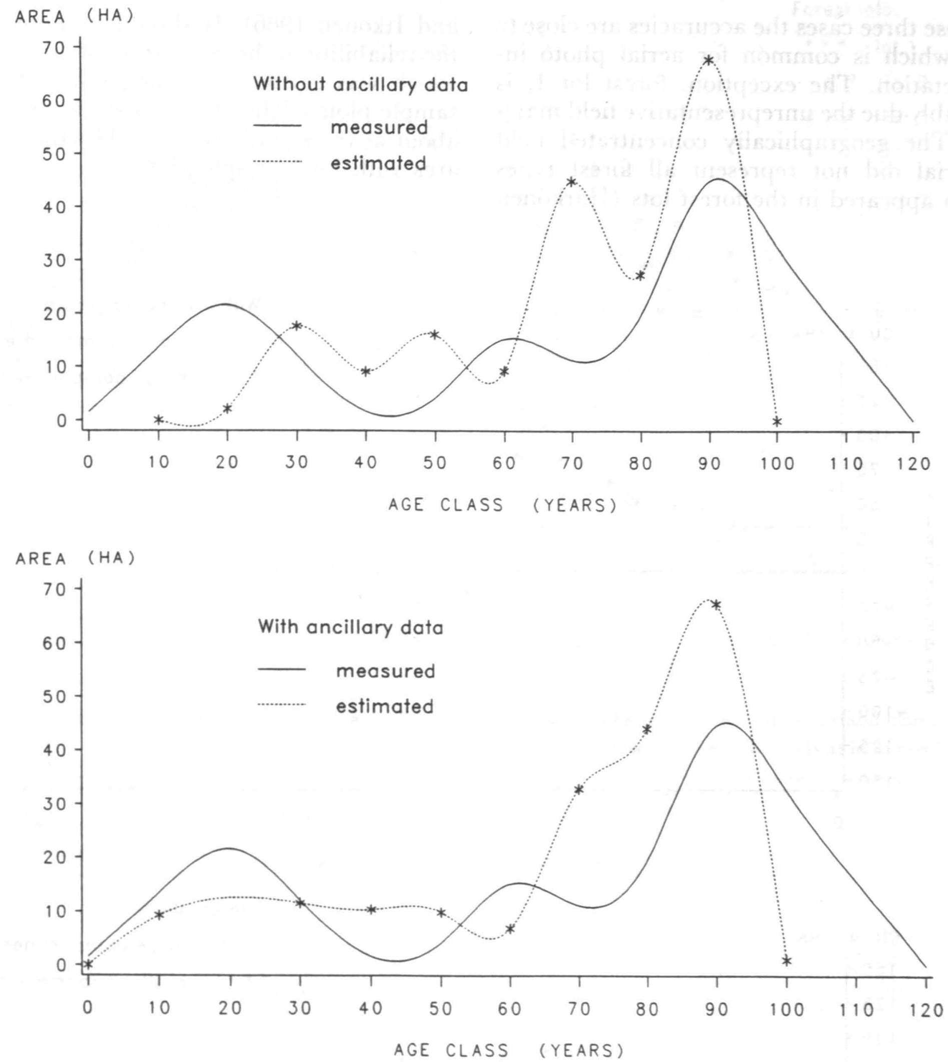

Figure 6. Comparison of satellite estimates and field measured results for compartmentwise ages when no ancillary information (upper part) and when ancillary data (lower part) was applied to the stratification.

$$(2) \quad c = \left(\sqrt{1/n \sum_{1}^{n} (x_i - \hat{x}_i)^2} \,/\, \bar{x}\right) \cdot 100$$

where

x_i = measured characteristic in the compartment i,

$\hat{x}_i$ = estimated characteristic in the compartment i,

n = number of compartments,

$\bar{x} = 1/n \sum_{1}^{n} x_i$

The results obtained for three forest lots are presented in Table 12. For comparison, the corresponding results for the Hyytiälä study area (Material 3) are included in the same table.

Figures 7 and 8 together with Table 12 give a overview of the current state of the method. Two features characteristic of the estimation procedure attract attention. First, some large errors occur. Secondly, the estimation accuracies do not vary a lot. According to Table 12 the accuracies can be considered to be at the same level in three of the four cases, and in these three cases the accuracies are close to that which is common for aerial photo interpretation. The exception, forest lot 1, is probably due the unrepresentative field material. The geographically concentrated field material did not represent all forest types which appeared in the forest lots (Härkönen and Itkonen 1986). It should be noted that the reliability in the estimation of forest lot 2, which was carried out using only 191 field sample plots of the Hyytiälä study area, was about at the same level as in Hyytiälä study area with 1403 sample plots.

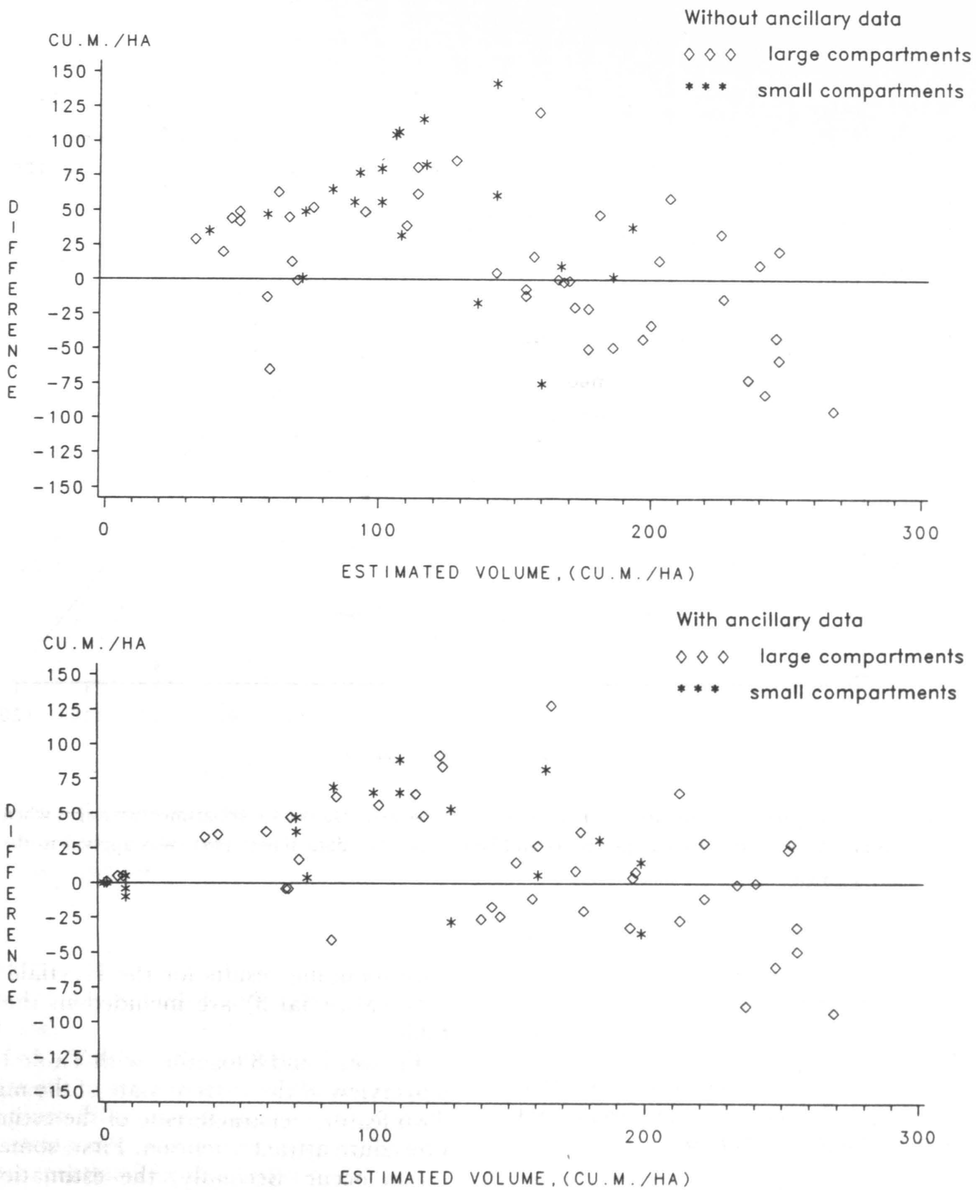

Figure 7. Comparison of estimated and field measured volumes by compartments without ancillary data (upper part) and with ancillary data (lower part). The compartments less than one hectare are classified as small.

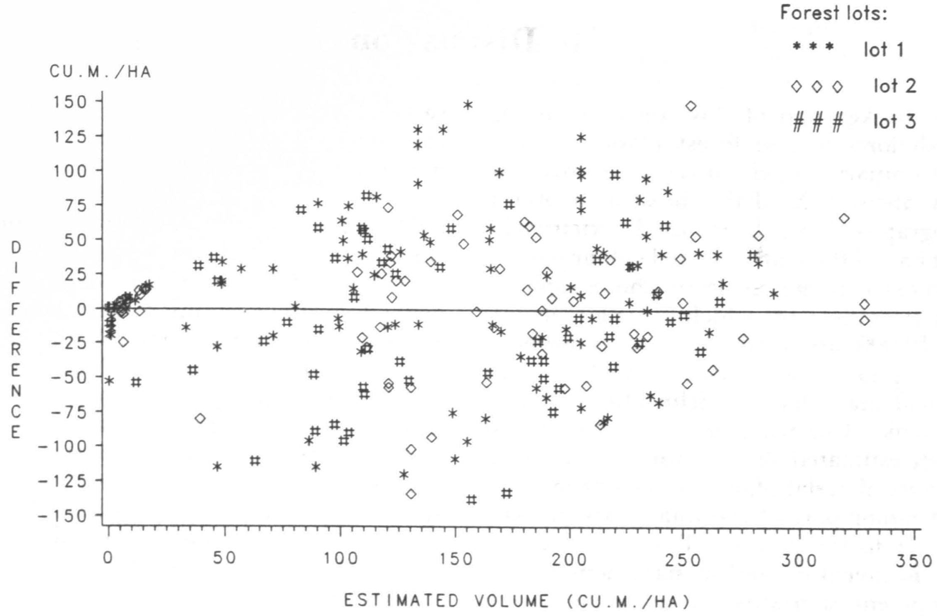

Figure 8. Comparison of estimated and field measured volumes by compartments for three forest lots.

Table 12. Some quality characteristics for compartmentwise estimates. The left column within a stand characteristic refers to all the compartments of the study area and the right one to those the size of which is at least one hectare.

Study area and quality characteristic	Forest stand charasteristic: Age		Volume	
Hyytiälä				
N:o of comp.	65	43	65	43
x	48	57	114	141
r	.87	.90	.87	.90
c (formula (2))	38	28	46	32
Forest lot 1				
N:o of comp.	102	62	102	62
x	63	64	128	141
r	.76	.75	.70	.77
c (formula (2))	36	36	55	46
Forest lot 2				
N:o of comp.	70	44	70	44
x	63	65	146	157
r	.76	.88	.88	.90
c (formula (2))	38	27	32	27
Forest lot 3				
N:o of comp.	68	53	68	53
x	54	61	137	155
r	.81	.73	.83	.78
c (formula (2))	34	32	38	36

6. Discussion

The background of this study lies in the Finnish forestry and forest planning situation. Compartmentwise inventories cover annually about 7 % of the forest area. Aerial photographs have been used extensively, about half of them are infrared colour photos. The most common scale of photography is about 1: 30 000 from which the enlargements to 1: 10 000 are made for the consumers. Aerial photos are used together with 1: 10 000 maps for the delineation of compartments. Compartmentwise characteristiscs are estimated almost entirely in the field. The costs of aerial photos as well as of maps are of minor part of the total costs, usually from five to ten percent. Therefore the tendency in inventory and management system development is towards a reduction of the cost of field work. For example, a drastic improvement in field work would take place if one man could cover eighty instead of forty hectares daily with sufficient accuracy of estimates.

Satellite imagery offer a promising means for making forest inventories and forest planning more efficient. To what extent the imagery can be used for inventory purposes at the operative level is still not clear. The results obtained wit Landsat MSS data usually did not meet the detailed information requirements of the forestry community. Consequently, only few European countries have had serious, long-term research programs on Landsat-applications (Jaakkola 1986). In Finland, the Technical Research Centre has been the most active and consistent in this field (see e.g. Kilpelä et al. 1978, Saukkola 1982, Häme and Saukkola 1982, Saukkola and Jaakkola 1983). The availability of Landsat TM and SPOT data will probably essentially improve the usability of satellite imagery, but it will also set additional requirements for satellite imagery interpretation. New methods of pattern recognition have been incorporated successfully to imagery based forest inventory in the Technical Research Centre (Tomppo 1987).

Against the background described above, the method presented, which originates from two phase sampling based on aerial photo interpretation, has in its simplicity worked satisfactorily. The application presented and experimented with here is close to that of the national forest inventories in northern Finland between 1970–78 (Poso and Kujala 1971, 1978). The principal ideas behind the work are as follows. First, all the characteristics required must be inventoried. The method must not set any restrictions as such. Secondly, the system is built on an old statistical methodology, i.e. two phase sampling. The first phase sampling units consist of systematic set of plots the intensity of which is arbitrary. The first phase units are to be supplied by radiation data from satellite imagery and possibly with other ancillary information from maps and aerial photos to be used in the stratification. The second phase consists of field measurements with a sufficient number of plots in each stratum.

The application of the method requires a sufficiently accurate location of pixels and plots, as well as the borderlines of compartments. A warning was given in this study (Section 5.1). A systematic correction of 30 m was made for the location of the sample plots in the case of Material 3, and a 20 m correction in the case of Material 5. In both cases, but especially for Material 3, this systematic movement of field and satellite data in relation to each other gave a distinctly better basis for the estimation. A suggested explanation was radial distortion characteristic of aerial photographs. The conclusion to be drawn are that the plots should be placed directly on the base map and accordingly geograpic location of satellite imagery should be performed separately for the areas of interest.

Landsat 5 TM material proved to give better results than Landsat 3 MSS material. The former material also showed high consistency (cf. Section 5.2). The dependence between the radiation values and the continuous stand characteristics in September 1984 and June 1985 materials were very close to each others when the radiation values were transformed to principal components.

The boundary units, be they either sample plots or satellite pixels, are problematic. In Materials 2 and 3 the plots which fell close to distinct borderlines were moved a further 10–20 m inside of the compartment to which the center of the plot belonged. After digitizing the borderlines it is easy to identify those plots and pixels which fall too close to borderlines. The proportion of "borderline pixels" in Material 3 was 25 %.

Other problems come from the fact that some compartments are small in size, i.e. smaller than one hectare. Especially, if the digitizing of boundary lines, plot coordinates and pixel centers do not coincide well, the proportion of plots belonging to wrong compartment or to the wrong pixel increases (Section 5.4).

In the calculation of radiation values for a plot, values of from one to four neighbour pixels were tried. No distinct differences in the usability of alternatives could be found. In the case of small compartments, however, the use of the nearest pixel alone is recommendable.

The ancillary information provided only modest improvement in the accuracy of the estimates for growing stock. However, some errors could be avoided by stratifying forest compartments into two volume categories from aerial photographs: i) treeless or very young plantations and ii) other categories. It was found in an early stage of the investigation that some open areas were mixed with high volume stands. The heterogeneity in open areas probably originate from different slash, grass and soil surface treatments. Some black areas may have been burned, for example. Map data used as ancillary information consisted of land and soil categories. Consequently, the highest benefit was recognized in soil classification.

The role of ancillary data could have been significantly greater. As long as the delineation is done from aerial photographs, it is possible to increase the role of preliminary stratification with minimal effort. Instead of using only two volume categories, had it been been possible to use three or four and this would probably have improved the precision of estimation results distinctly. Some other criteria such as main tree species or development class could also have been applicable. This kind preliminary stratification is not even time consuming when compared with the delineation or digitizing work. Other sources for ancillary information to be considered are, for example, textural features of the imagery (see e.g. Heinonen et al. 1985 and Tomppo 1987 and the references therein), topographic data from maps, and data from old inventories.

The original radiation values were transformed to principal component values which were then used for the stratification. The three first components accounted 92–98 % of the variation of all Landsat 5 TM channels when concerning rather homogenuous forest land. It also turned out that the covariance matrix gave somewhat better results than the correlation matrix. The former gives more weight to those channels in which there are the highest variations (cf. Singh and Harrison 1985). In Landsat 5 TM the highest variations existed in channels 4 and 5 (near infrared channels). The correlation matrices indicated that radiation values of channel 4 had highest correlation coefficients with the most important stand characteristics.

The plot size employed in the study, a relascope plot with basal area factor 2 (one tree = 2 (one tree = 2 m^2/ha or maximum distance of a tree to be included in the plot is 35.36 times the breast height diameter of the tree), is rather small. Comparing the results from Material 3 and 4 it becomes obvious that the correlation of radiation values with stand characteristics can be improved significantly by increasing the size of the sampling plot. Some conclusions was made also by Parkkonen (1984) whose study dealt with cluster size.

In assessing the optimum size for a plot the danger exists that too much weight will be placed on correlation coefficients. If the objective is to estimate compartment characteristics to sufficient accuracy one should also look at costs. There is no way to estimate whether the plots used here are too small or not.

The methodology described can be applied flexibly, i.e. it can be applied fairly easily to various inventories configurations. It is essential to ensure that all output data are based on field measured data. Which plots or plot combinations are to be used for estimation of any specific object depends on the stratification and thereby on satellite information. It can be concluded that the application of the methodology requires more than hundred field sample plots in order to determine all of the important data combinations which should be known for forest planning. On the other hand, two hundred sample plots constituted a sufficient second phase sample (see Section 5.5).

The measurement of field plots is expensive so the important question is how to make them. The answer probably depends on the situation. In one case it may be sensible to measure and remeasure permanent sample plots, in another case separate, specific field measurements may be the best choise. Another possibility is to utilize measurements made for other purposes, plots of national forest inventory, for example. For these and other questions experimentation on a practical scale gives the most reliable answers.

The two phase sampling, as it was applied here to a compartmentwise forest inventory, seems to work without any major difficulties. It can be concluded that the method is easily applicable to inventories based on the use of sample plots without compartments, as in many regional and national forest inventories. The final solution for the arrangement of an inventory depends on the objectives and the background. However, there are plenty of details or alternative solutions in the application which should be studied. The system may consist of successive inventories, permanent sample plots, updating procedures, etc. Peng (1987) has applied the method described in his study to integrating multitemporal imagery data with permanent sample plots. He has also made some valuable comparisons between this method and different kinds of regression techniques, as well as for quantitative and qualitative stand characteristics.

The results concerning the reliability of estimates obtained with Landsat TM material cannot be generalized. The test area was small, less than 200 hectares, and thus the field material was concentrated in a way which is not possible or recommendable in practise.

The question which arises with the use of satellite imagery whether the reliability of estimates is good enough or not for a compartmentwise forest inventory. The answer is not a simple one. One should take into account that the other alternatives, aerial photo interpretation and occular field estimation often produce high errors. The combination of procedures is one solution for an improved inventory.

A significant feature in the evaluation of the usability of satellite imagery for updating purposes deals with the dependance of errors obtained for first phase sample units of successive inventories. If the dependance is distinct, the estimates for changes are more accurate than those assessed on the basis of separate independent inventories.

7. Summary

A forest inventory method using satellite as well as other ancillary information is decribed and tested. The method is based on two phase sampling, i.e., a large number of first phase sample plots are stratified by ancillary information a part of which is also measured in the field. Thus, the method has not much common with supervised classification, the procedure often applied in connection with satellite imagery.

The method was tested using eight materials consisting of three sets of field plots, over 2000 in total number, and of two Landsat 3 MSS imageries, as well as two Landsat 5 TM imageries.

Correlation tables showed the highest coefficients for stand characteristics of mean volume, mean height, and mean age. The highest average coefficients for volume and age and for Landsat 3 MSS imagery were –.40 (MSS–6) and –.43 (first principal component). For Landsat 5 TM imagery the respective average correlation coefficients were –.60 (channel 4) and –.63 (first principal component). The coefficients are valid for relascope plots. For larger rectangular plots TM channel 4 gave the highest correlation coefficient, –.77, whereas the first principal component gave "only" –.68.

The location of plots was more accurate

with TM material of higher spatial resolution than with the MSS material. The respective standard deviations of errors were estimated as 10–15 m and 20–30 m. One source of errors was the ground or radial distortion of the aerial photograph on which the plots were first located.

Central to the method is the stratification of the first phase sampling units. The proportion of within stratum variance from the total variance was regarded as an applicable measure of success. The results showed proportions of about 80 % for MSS material and about 60 % for TM when mean volume and age from relascope plots were studied. The percentages could be improved, i.e., decreased by using extra ancillary information from maps and aerial photographs.

Most of the stratifications were made using 15 strata. This number is high enough or even too high when only satellite imagery is used for the stratification. The number could be increased if map- and aerial photo-data are also used for stratification. According to the results, 20–25 strata are recommendable in this case. It seems justifiable that the number of strata should be increased when the extent of the inventory is increased.

The specific objective of the experimentation was the inventory of compartmentwise stand characteristics. The compartments were delineated on aerial photographs and their size varied from 0.3 to 27.0 hectares. The reliability of estimates increased with the increase of compartment size and the consequent number of sample units. In fact, the size of a compartment can be regarded as arbitrary. Accordingly, a compartment may be a large region of some million hectares, for example.

A relascope plot is a relatively small unit to give high correlations between the satellite and field measured forest characteristics. On the other hand, this handicap can be largely substituted by the increase of the number of the plots. The optimal size for a plot cannot be estimated on the basis of the material used but it might be a little larger than the relascope plot with basal area factor 2 of study (one tree represents 2 sq. meters per hectare).

The ultimate conclusions concerning the applicability of the methodology is based on a comparison of the estimated and field measured characteristics for compartments, Sections 5.4 and 5.5. The correlation coefficients for the mean volume, age and mean height vary from .84 to .91 for the Hyytiälä study area. According to the results from Hyytiälä and from the three forest lots, the estimation accuracy for the continuous stand characteristics can be regarded as comparable with those often obtained by ocular field estimation or by aerial photo interpretation. Other results, such as estimates for tree species distribution, are, however less satisfactory.

Some reservations are in order. First, the use of satellite imagery may be good for estimating some characteristics rather than others. Secondly, the material of this study was georgraphically fairly concentrated and generalizations are risky. Thirdly, there is a tendency to underestimate those compartments which are above the population mean whereas the opposite is true to the compartments which are less than the population mean.

In spite of these reservations, the methodology together with Landsat 5 TM material is promising. It is flexible in offering many alternative choices in defining the first and second phase samples, as well as the sources for stratification. Connecting permanent sample plots and old inventory data for updating purposes in the form of continuous forest inventory seems feasible. More experimentation is required in varying practical conditions.

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