FOREST INVENTORY BY MEANS OF TREE-WISE 3D-MEASUREMENTS OF LASER SCANNING DATA AND DIGITAL AERIAL PHOTOGRAPHS

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ABSTRACT:

Two of the most promising new remote sensing technologies for increasing accuracy and efficiency of forest inventory are tree-wise or stand-wise measurements of airborne laser scanner data or 2- (2D) and 3-dimensional measurements (3D) of digital aerial photographs. The aim of the study was to compare 3D measurements of digital aerial photographs and laser scanning to 2D measurements of digital aerial photographs and traditional compartment-wise inventory. Comparison was based on the expected net present value (NPV) losses. Reference data was measured from Central Park of Helsinki, Finland. The results showed without inventory costs there was not any significant difference between the expected NPV losses of 3D measurements of digital aerial photographs and laser scanning and compartment-wise inventory method. Due to the small size of study area (700 ha) the costs of remote sensing techniques increased considerably and compartment-wise inventory method was the most cost-effective when accounting for inventory costs. However, if the inventory area had been over 20 km^2, the expected NPV losses of 3D and compartment-wise inventory methods would have been similar. Also in 2D method the costs decrease with respect to the size of the area. When accounting NPV losses 3D and compartment-wise methods produce always better results than 2D method due to better accuracies.

1. INTRODUCTION

Reliable inventory data is essential for forest planning. Usually the future expectations focus only on the state of harvest costs and timber prices and less on the losses caused by incorrect estimation of stand variables. When assessing the state of a stand it is possible the estimates of an inventory method can differ significantly from the real situation.

Compartment-wise inventory is widely used inventory method in Finland both in public and private owned forests. The basic unit of forest inventory is a forest stand, which is used as management planning unit. The size of a forest stand is normally 0.5-2 hectares. Forest stand is defined as a homogenous area according to relevant stand characteristics, e.g. the site fertility, composition of tree species, and stand age. Forest inventory data is mostly collected by means of field surveys, which are both expensive and time-consuming. The method is also sensitive to subjective measurement errors. Remote sensing is normally used no more than for delineation of compartment boundaries. The total costs of compartment-wise inventory in Finland were 17.9 €/ha in year 2000, of which 7.9 €/ha, i.e. 45 per cent of the costs, consisted of field measurements (Uuttera et al. 2002).

Two of the most promising new remote sensing technologies for increasing accuracy and efficiency of forest inventory are tree-wise or stand-wise measurements of airborne laser scanner data or (3D) digital aerial photographs. The present state of the art of these technologies indicates high potential in assessing various parameters of single trees, and adapting this information for plot and stand level. The height of individual trees can be measured at the best with an accuracy of 50 cm. At stand level, basal area and stem volume can be obtained with a standard error of about 10 % if the relation between height and diameter of the tree is solved appropriately. The use of the distribution function can be of help in assessing the amount of wood in the second and third storeys. Tree species can be obtained with the help of the aerial imagery to about 80-90 % correctness for individual trees (Korpela 2004). Using multi-temporal data sets it has been shown that even the plotwise growth of trees can determined with about 10 cm precision using laser scanner (based on 2 years separation in laser acquisitions). The corresponding value for standwise growth is 5 cm. All mature cut or fallen trees can be automatically detected. In addition, laser survey provides a DEM with accuracy between 20 and 40 cm in hilly, forested areas.

Laser scanning provides 3-dimensional information from the object. Recent developments in laser scanners, GPS-systems, and laser technique have made the development of laser scanning in forest planning possible. The first research to compare laser-derived forest inventory estimates to estimates of other remote sensing inventory methods in a single test site was carried out by Hyyppä and Hyyppä (1999). They discovered laser-derived attributes were more accurate than those obtained with other remote sensing inventory methods. The results showed also that laser scanning is the only remote sensing method that fills the requirements of accuracy in operative stand-wise forest inventory. The accuracy of laser scanning estimates in tree, plot, and stand levels is very similar or even better than those achieved in traditional field inventory (Holmgren 2003, Naesset 2004).

There are several 2D approaches for interpreting tree crowns on high resolution imagery. A crown model can be derived and corresponding instances on the image can be searched for. Problems stem however from the fact that crown images vary greatly depending on crown illumination and location in the image. Another alternative is to analyze the image statistically in order to identify pixel sets having high grey tones and to assume they depict actual tree crowns. This approach is in turn highly dependent of the imaging scale and conditions. The image can also be statistically divided into segments representing crowns and non-crowns. Furthermore boarders between illuminated crowns and intermediate areas can be searched for. Finally combinations of these approaches can be used.

Korpela (2004) presented a new forest inventory method in which multiple digitised aerial photographs are used for manual and semi-automatic 3D positioning of tree tops, for species classification, and for measurements on tree height and crown width. With the 3D inventory method it is possible to achieve better accuracies than with an inventory method based on 2D method (Uuttera et al. 2002, Korpela 2004, Korpela and Tokola 2004). Korpela and Tokola (2004) examined differences in 2D and 3D aerial photography based estimations and pointed out the 2D scheme is more prone to systematic errors in mean crown diameter and mean diameters of trees. Compared to field measurements, where measuring pace is 15-20 trees per hour, with 3D-method it is possible measure 40-80 trees per hour if measuring all trees manually.

New remote sensing techniques are, however, expensive. The costs of aerial laser scanning data acquisition depend on the size of the survey area (Figure 1). Data acquisition and preprocessing of laser scanning costs about 40 000-50 000 €, and mobilisation costs are roughly 12 000 € (Holopainen and Hyyppä 2003). On the other hand, the costs are all the time decreasing because of improvements in availability of laser scanner and technological development. If it is possible to achieve more exact treatment chains with the help of accurate and update information, new remote sensing techniques are promising alternatives to forest inventory.

The costs of medium-scale aerial photographs (1:12000-1:16000) are approximately 1-2 €/ha assuming 60 % forward and side overlaps for large projects (Korpela 2004).

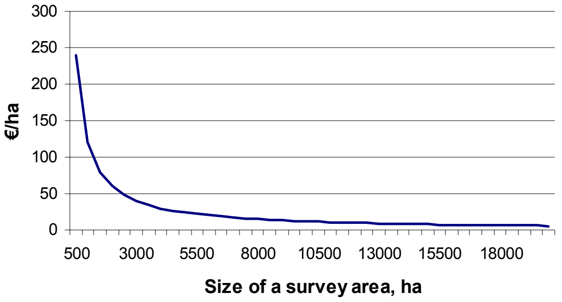

Figure 1. The costs ha^{-1} of laser scanning as a function of the size of the survey area.

Eid (2000) examined the impact of errorneous initial description of forest stand variables to final harvest decisions with means of expected net present value losses. The expected net present value (NPV) is one of the most common profitability criteria in forest planning and is a powerful tool in valuing forest properties (Klemperer 1996). NPV is described as the present value of revenues subtracted the present value of costs. If NPV is positive, the investment is profitable with the discount rate used. In forest planning, 3 and 5 per cent discount rates are normally used for profitability calculations.

The aim of the study was to compare 3D measurements of digital aerial photographs and laser scanning to compartment-wise inventory and 2D measurements of digital aerial photographs. Comparison was based on the expected NPV losses that consisted of the inventory costs and incorrect timings of treatments. The reference data consisted of stand-wise information measured from the study area.

2. MATERIAL AND METHODS

2.1 Study data

The study area is part of the forests of Helsinki city area called Central Park . The Central Park is a recreational area of Helsinki whose forests are managed in order to preserve biodiversity in spite of environmental stress and heavy recreational use. The area is 700 hectares, of which forested area is 684 hectares. The forest is predominantly old-growth stands in fertile soil forest types, and most stands are dominated by Norway spruce (*Picea Abies* (L.) Karst.) (49 % of the forested area, Table 2). Other main tree species are Scots pine (*Pinus sylvestris* L.) and birch (*Betula pendula* Roth).

The descriptive statistics of the data is represented in Table 3. Mean volume was 175.8 m^3 ha^{-1}, and mean basal area was 20.2 m^2/ha. Mean height was 18.6 m with standard error of 7.4 meters. Mean diameter was 25.1 cm, and mean number of stems per hectare was 1156 stems ha^{-1}. The mean age of stands was 68 years old when the oldest stands were 127 years old. In Table 4 is shown area and volume distributions in different development classes.

Variable	Mean	SD
H, m	18.6	7.4
$D_{1.3}$, cm	25.1	10.8
G, m^2 ha^{-1}	20.2	11.7
N, ha^{-1}	1156	1593
V, m^3 ha^{-1}	175.8	95.7

Table 3. The mean values and standard deviations (SD) of the data.

Site	Pine		Spruce		Birch		Total, ha	
1	0.0	*0.0*	3.5	*0.5*	17.4	*2.5*	20.9	*3.1*
2	16.9	*2.5*	174.3	*25.5*	119.0	*17.4*	310.2	*45.4*
3	33.3	*4.9*	154.4	*22.6*	51.4	*7.5*	239.1	*35.0*
4	43.1	*6.3*	5.9	*0.9*	6.2	*0.9*	55.2	*8.1*
5	16.3	*2.4*	0.0	*0.0*	0.7	*0.1*	17.0	*2.5*
6	0.3	*0.0*	0.0	*0.0*	0.1	*0.0*	0.4	*0.1*
7	40.1	*5.9*	0.0	*0.0*	1.0	*0.1*	41.1	*6.0*
Total, ha	150.0	*21.9*	338.1	*49.4*	195.8	*28.6*	683.9	*100.0*

Table 2. Distribution of field data into site classes and main species. Proportion in percentages seen in italics.

Dev. Class	**area, ha**	*%*	**vol, m^3/ha**
T1	1.4	*0.2*	0.7
T2	20.6	*3.0*	17.1
02	65.7	*9.6*	98.6
03	168.9	*24.7*	180.5
04	392.1	*57.3*	199.2
05	7.7	*1.1*	225.7
Y1	26.4	*3.9*	114.3
S0	1.1	*0.2*	53.3
total	683.9	*100.0*	175.8

Table 4. Stand area and mean volume distribution in development classes. T1=seedling stand (height < 1.3 m), T2=young reproduction stand (dbh < 8 cm), 02=young stand (dbh 8-16 cm), 03=middle aged stand (dbh < 16 cm, but less than in mature stand), 04=mature stand (mean dbh or age has reached the maturity criteria depending on species and site index), 05=shelter wood stand, Y1=seedling stands with hold-over trees, S0=stands in seed-tree position.

The data was standwise information of the area. The stand variables used in the study were forest site type, main species, stem number ha^{-1}, stand age at breast height, mean diameter, and mean height. The data measured in field from the area was taken as reference data.

2.2. Methods

The accuracies of 3D measurements of digital aerial photographs and laser scanning are very similar (Holmgren 2003, Korpela 2004, Naesset 2004) and they were therefore considered in this study as one method (Table 5).

In Finland, there has been much research about the accuracies of compartment-wise inventory (e.g. Poso 1983, Suutarla 1985, Pilhjerta 1987, Pigg 1994, Poso 1994, Koivuniemi 2003). The accuracies of compartment-wise inventory shown in Table 3 are rough approximates and can be achieved in stands that are in development phase between young to mature (Uuttera et al. 2002).

Allometric models are used to estimate the stem size of a tree in digital aerial photographs. Depending of the amount of variables used in the model and tree species, the accuracy of a tree diameter estimate varies between 10 and 25 per cent (Kalliovirta and Tokola 2004). Trees in the upper canopy level are visible in the photographs and are possible to measure; tree distribution in lower canopy level has to be derived.

The data was simulated to final cut with MOTTI-simulator In addition to general stand information (location, forest site, main species, previous forestry operations etc.), the simulator requires tree- or stand level data (number of stems ha^{-1}, height, diameter, age at breast height, optionally crown ratio). If only stand-level information is available, diameter distribution is created automatically. (See further details in Salminen et al. 2004). The definitions of final cut of different main species and forest sites were those of Forestry Development Centre Tapio and that are generally used in Finland. For the costs and assortment prices used, the costs of thinning were 12.46 €/m^3 and final cut 6.95 €/m^3 in Finland in year 2002 (Örn 2002), and the prices of logs and pulpwood are the prices of Helsinki region in year 2003 (Table 6).

The stands were classified by main tree species, development class, and site index. The groups were 63 in number, of which 2 were stands in seed-tree position, 3 shelter wood stands and 7 seedling stands with hold-over trees, that were not taken into simulations. In addition, seedling stands and young reproduction stands were left out. A total of 40 stands were selected to the study. Each stand was simulated to final cut . With the other inventory methods, it was assumed that site classes, main species and development classes were known. All deciduous tree species were assumed as birch.

The stand variables of the classes for different inventory methods were defined with the intention that every inventory method had both upper and lower limits in data with respect to its accuracy. Only the lower accuracy limit of stems ha^{-1} was used for both 2D and 3D digital aerial photographs since the estimate of the variable is in all cases underestimate due to low discernibility rate of suppressed trees (e.g. Maltamo et al. 2003,Korpela 2004). The estimate measured from field was taken for upper limit of stems ha^{-1}. The data was simulated for five-year periods with upper and lower limits of inventory methods using the same treatment criteria as with reference data. Using the treatment schedule and timing of a given inventory method, the reference data was simulated another time. The results of the latter simulations correspond the expected yield of a real stand when thinning and final cut are carried out according to given inventory method.

Wood prices in Helsinki in year 2003, €/m^3		
	Log	Pulp
Pine	44.6	12.8
Spruce	43.9	21.8
Birch	41	11.9

Table 6. Prices of wood assortments by species in Helsinki region in year 2003.

The differences of yield between inventory methods and reference data were analysed using expected NPV losses. The expected NPV loss in stand *i* with an inventory method *j* was calculated as

$$NPVloss_{ij} = NPV_{reference\,i} - NPV_{invmethod\,ij} \quad (1)$$

The NPV loss per hectare for an inventory method *j* was calculated as

$$NPVloss_{j} = \frac{1}{n}\sum_{i=1}^{n} NPVloss_{ij} \quad (2)$$

The average value of the expected NPV losses from upper and lower limits was used when comparing the inventory methods.

	3D and laser scanning			*Compartment-wise inventory*			*2D aerial photograph*		
	Pine	*Spruce*	*Birch*	*Pine*	*Spruce*	*Birch*	*Pine*	*Spruce*	*Birch*
d_{gM} (cm)	0.15	0.15	0.15	0.15	0.15	0.18	0.20	0.20	0.23
h_{gM} (m)	0.04	0.04	0.04	0.15	0.15	0.18	0.20	0.20	0.23
n/ha	0.20	0.20	0.20	0.20	0.20	0.23	0.65	0.65	0.70
age (a)	0.20	0.20	0.30	0.25	0.28	0.25	0.20	0.20	0.30

Table 5. The accuracies (rmse %) of different inventory methods (Tokola et al. 1998, Uuttera et al. 2002, Korpela 2004, Naesset 2004)

4. Results

In reference data the expected NPV using 3 % and 5 % discount rates were 8 880 € ha^{-1} and 8 473 € ha^{-1}, respectively. With other inventory methods, the expected NPV values differed considerably. The biggest variation between lower and upper limit had 2D measurements of digital aerial photographs, which was a consequence of biggest variation in variable accuracies.

Without inventory costs, the expected NPV losses of 3D measurements of digital aerial photographs and laser scanning were with 3 % and 5 % discount rates 387 € ha^{-1} and 512 € ha^{-1}, respectively (Figure 7). Compartment-wise inventory had slightly smaller NPV losses than 3-dimensional inventory methods. 2D digital aerial photographs had the biggest NPV losses. When taking into account inventory costs, compartment-wise inventory proved most efficient (Figure 8). However, usually forest inventories are directed to large areas when remote sensing methods decrease in costs (cf. Figure 1). Laser scanner data to the study area would cost 191 €/ha if the inventory was carried out only in that area. If the area studied had been for example 20 km^2, the expected NPV losses of 3-dimensional and compartment-wise inventory methods would have been similar. Also in 2D method, inventory costs decrease with respect to the size of the area. When inventory area is larger than 8,5 km^2 the inventory costs of 2D method are smaller than 3D and compartment-wise methods. However, when accounting NPV losses 3D and compartment-wise methods produce always better results due to better accuracies.

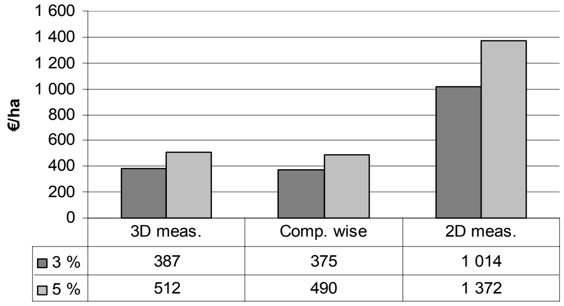

Figure 7. Without inventory costs, the expected NPV losses per hectare of different inventory methods in the area studied. Discount rates 3 and 5 per cent.

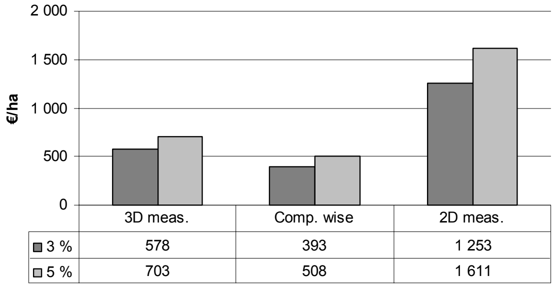

Figure 8. Inventory costs included, the expected NPV losses per hectare of different inventory methods in the area studied. Discount rates 3 and 5 per cent.

Biggest NPV losses were in middle aged spruce stands and mature birch stands (Table 7). If NPV loss is negative, the treatment timings for a given inventory method would lead to more cost-efficient solution than reference data.

The amount of thinnings was the same regardless of an inventory method. As expected, thinnings and final cut were proposed to carry out earlier if the state of a stand were overestimated, and vice versa. However, the expected NPV values of overestimated stand data for all inventory methods were in most stands greater than that of reference data. This is due to the degree of a discount rate that was in this study 3 % and 5 %; with 2 % discount rate the expected NPV of reference data would have been greater than other inventory methods in most cases. From economical point of view, the bigger the rate of degree is the sooner the final felling should carry out.

5. DISCUSSION

Compartment-wise inventory had smallest NPV losses of all inventory methods. Remote sensing inventory methods are more effective when examining large areas. The area studied was small (700 hectares) and therefore the acquisition costs of remote sensing techniques ha^{-1} were significant. Normally inventories are focused on larger, over 10 km^2 areas that decreases costs of remote sensing material and photo interpretation. According to our results, if the inventory area had been 20 km^2, the expected NPV losses of 3-dimensional and compartment-wise inventory methods would have been similar. In 2D method the costs decrease with respect to the size of the area. When accounting NPV losses 3D and compartment-wise methods produce always better results than 2D method due to better accuracies.

In addition to the size of the study area, the costs of digital aerial photographs depend on the amount, overlaps, and the scale of photographs. The costs of laser scanning depend on the flight altitude, the size and the shape of the test area.

The results of this study is directly based on the accuracies used (Table 3). Main species and site recognition were assumed to succeed with 100 per cent accuracy. In reality, the accuracy in species recognition with 2D and 3D digital aerial photographs, and laser scanning is 60-90 % (Haara and Haarala 2002), 78-90 % (Korpela 2004, s.81), and 95 % (for coniferous trees, Holmgren and Persson 2004), respectively. Incorrect species recognition inflicts on random effects in diameter and volume estimations (Korpela and Tokola 2004). Moreover, the accuracy in species recognition needs to be over 85 per cent so that the errors caused by averaging would not be significant (Korpela and Tokola 2004). Correct species recognition is required if aiming to accurate estimates e.g. in timber assortments, since growth models and calculation of timber volumes are usually species dependent.

Compartment-wise inventory produces information at stand-level. However, tree-level data describes the stand structure

		3D measurements		Compartment-wise		2D photographs	
Dev. Class	**Species**	**3 %**	**5 %**	**3 %**	**5 %**	**3 %**	**5 %**
02	Pine	71	54	71	35	150	114
02	Spruce	801	646	792	638	1 076	826
02	Birch	121	60	73	21	-506	-353
03	Pine	-235	-247	-237	-195	387	603
03	Spruce	1 449	1 176	1 255	1 012	1 786	1 573
03	Birch	-812	-410	-350	-27	-356	2
04	Pine	637	916	471	683	450	640
04	Spruce	17	28	12	20	1 242	1 727
04	Birch	1 436	2 091	1 428	2 068	2 323	3 268

Table 9. The expected NPV losses in development classes by species.

more specifically into timber assortments and species distribution. If species-wise diameter distribution is required, accuracy at tree level needs to be high (Korpela and Tokola 2004).

Since 3D data (laser scanning data or data derived by digital photogrammetry) is rather expensive for the large areas, it is worth examining as a sampling device (Holopainen and Hyyppä 2003). The most economic use of the laser scanning in forestry is to apply it on a strip-base sampling, since long stripes are economic to fly. Thus, large-area forest inventory using permanent or non-permanent sample plots are perhaps the most feasible operative applications for laser scanning at single tree level. Furthermore, laser scanning sample could be utilized in compartment-wise forest inventory if some cheaper remote sensing material (e.g. digital aerial photographs) is available for generalising laser scanning result to whole forest area.

The usability of remote sensing based forest inventory in practise is dependent on amount of field work. Assuming the accuracy of 3D data in estimating forest variables such as tree hight, diameter, basal area, and volume of trees is as high as in previous research, and that accuracy of tree species recognition using digital aerial photographs is sufficient, volume of stand, tree species and timber assortment distributions would be possible to estimate without field measurements. In addition, growth of the trees and site quality would be possible to measure using multi-temporal laser scanning data.

However, field measurements would still be needed in calibration, determination of stand treatments, and in assessment biodiversity indicators or key biotopes. In future research the possibilities of new remote sensing methods for these issues should be evaluated. For example, it would be possible to map potentially important areas of biodiversity using tree height maps estimated by 3D methods or using fragmentation indicators estimated by 2D methods. Field measurements can be concentrated to those areas, and e.g. adaptive cluster sampling (e.g. Thompson 1990, 1991) could be utilized.

A major factor effecting the accuracy of numerical image interpretation is the accuracy of the ground truth data used. The standard error of e.g. stand data derived from compartment-wise inventories, commonly used as ground truth data, has turned out to be as high as 25% (Hyyppä 1998), which naturally is transferred also to the interpretation accuracy. Ground truth errors may in fact be even larger than the actual interpretation errors. It is therefore utmost important to improve the accuracy of ground truth data.

Modern measuring equipment provides a worthy means also for improving the efficiency and accuracy of field measurements. Today field measurements are carried out with the aid of field computers and satellite positioning systems with which measured forest data can be transferred directly to forest databases attached with accurate positioning data. Devices for improving the efficiency and accuracy of stock measurements have also been developed. The Helsinki University Dept. of Forest Management has e.g. developed a new stock measurement device called the laser-relascope that is based on laser measurements of angles and distances. The device can be used to measure tree heights and tree diameters at arbitrary heights from plot centers without actually visiting the trees. All measurements are further positioned using GPS (Laasasenaho et al. 2002).

References from journals:

Eid, T. 2000. Use of Uncertain Inventory Data in Forestry Scenario Models and Consequential Incorrect Harvest Decisions. Silva Fennica 34(2):89-100.

Haara, A., Haarala, M. 2002. Tree Species Classification using Semi-automatic Delineation of Trees on Aerial Images. Scandinavian Journal of Forest Research 17: 556-565.

Holmgren, J. 2003. Estimation of Forest Variables using Airborne Laser Scanning. Doctoral dissertation. Acta Universitatis Agriculturae Sueciae. Silvestria 278. SLU, Umeå, Sweden. 43 p.

Holmgren, J., Persson, Å. 2004. Identifying Species of Individual Trees Using Airborne Laser Scanner. Remote Sensing of Environment 90: 415-423.

Holopainen, M., Hyyppä, J. 2003. Possibilities with Laser Scanning in Practical Forestry. Proceedings from the ScandLaser Conference. Umeå, pages 264-273.

Hyyppä, H., Hyyppä, J. 1999. Comparing the accuracy of laser scanner with other optical remote sensing data sources for stand attribute retrieval. In: The Photogrammetric Journal of Finland. Vol. 16 No 2: 5-15.

Kalliovirta, J., Tokola, T. 2004. Functions for estimating stem diameter and age of tree using the crown length, height and existing stand register information. Manuscript for journal publication.

Koivuniemi, J. 2003. The accuracy of the compartmentwise forest inventory based on stands and located sample plots. PhD-thesis. University of Helsinki. Department of Forest Resource Management. 159 p. (In Finnish with English summary)

Korpela, I. 2004. Individual Tree Measurements by Means of Digital Aerial Photogrammetry. PhD-thesis. Silva Fennica. Monographs 3. 93 p.

Korpela, I. Tokola, T. 2004. Comparison of Alternatives Estimation Chains for Sinlge Tree based Forest Inventory Using Digitised Aerial Photography – a Simulation Approach. Manuscript for journal publication.

Laasasenaho, J., Koivuniemi, J., Melkas, T. & Räty, M. 2002. Puuston mittausetäisyyden- ja kulmanmittauslaitteella. Metsätieteen aikakauskirja 3/2002:523-530.

Naesset, E. 2004. Practical Large-scale Forest Stand Inventory Using a Small-footprint Airborne Scanning Laser. In: Scandinavian Journal of Forest Research 19: 164-179.

Poso, S. 1983. Kuvioittaisen arvioimismenetelmän perusteita. Silva Fennica 17(4): 313-349. (In Finnish)

Salminen, H., Lehtonen, M., Hynynen, J. 2004. Reusing legacy Fortran in the MOTTI growth and yield simulator. Accepted for publication in Computers and Electronics in Agriculture.

Uuttera, J., Hiltunen, J., Rissanen, P., Anttila, P., Hyvönen, P. 2002. Uudet kuvioittaisen arvioinnin menetelmät – Arvio soveltuvuudesta yksityismaiden metsäsuunnitteluun. Metsätieteen aikakauskirja 3/2002: 523-531. (In Finnish)

Thompson, S. K. 1990. Adaptive Cluster Sampling. Journal of American Statistical Association Vol 85, No 412: 1050-1059.

Thompson, S. K. 1991. Stratified Adaptive Cluster Sampling. Biometrika Vol 78, No 2: 389-397.

References from books:
Klemperer, W., D. 1996. Forest Resource Economics and Finance. Virginia Polytechnic Institute and State University College of Forestry and Wildlife Resources.

Tokola, T., Hyppänen, H., Miina, S., Vesa, L., Anttila, P. 1998. Metsän kaukokartoitus. Silva Carelica 32. University of Joensuu. 156 p. (In Finnish)

References from other literature:
Hyyppä, J. 1998. Uudet menetelmät metsien kaukokartoituksessa. Kaukokartoituksen teknologiaohjelman GLOBE-2000 hanke. Tekninen loppuraportti.

Pigg, J. 1994. Keskiläpimitan ja puutavaralajijakauman sekä muiden puustotunnusten tarkkuus Metsähallituksen kuvioittaisessa arvioinnissa. Master’s Thesis in Forest Mensuration and Management. 92 p. (In Finnish)

Pilhjerta, K. 1987. Puustotunnusten arviointivirheiden vaikutus kuvioittaisiin toimenpidevalintoihin MELAssa. University of Joensuu. 68 p. (In Finnish)

Poso. S. 1994. Metsätalouden suunnittelun perusteet. University of Helsinki, Department of Forest Resource Management. Publications 5. 155 p.

Suutarla, T. 1985. Kuvioittaisen arvioinnin päivitys ja sen luotettavuus. Master’s Thesis. University of Helsinki. Department of Forest Resource Management. 47 p. (In Finnish)

Örn, J. 2002. Puunkorjuun ja puutavaran kaukokuljetuksen suoritteet ja kustannukset vuonna 2002. Metsäteho. Tilastoliite. (In Finnish)

References from websites:
Metsätilastoja. 2004. MTK annual report 2003. http://www.mtk.fi/default.asp?path=2918,34241(accessed 5 July 2004, in Finnish)

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