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Effect of Data Acquisition Accuracy on Timing of Stand Harvests and Expected Net Present Value

Markus Holopainen and Mervi Talvitie

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Modern remote sensing provides cost-efficient spatial digital data that are more accurate than before. However, the influence of increased accuracy and cost-efficiency on simulations of forest management planning has not been evaluated. The aim of the present study was to analyse the effect of data acquisition accuracy on standwise forest inventory by comparing the accuracy and cost of traditional compartmentwise inventory methods with 2D and 3D measurements of digital aerial photographs and airborne laser scanning. Comparison was based on the expected net present value (NPV), i.e. economic losses that consisted of the inventory costs and incorrect timings of treatments. The reference data, totalling 700 ha, were measured from Central Park in the city of Helsinki, Finland. The data were simulated to final cut with a MOTTI simulator, which is a stand-level analysis tool that can be used to assess the effects of alternative forest management practices on growth and timber yield. The results showed that when inventory costs were not considered there were no significant differences between the expected NPV losses in 3D measurements of digital aerial photographs, laser scanning and the compartmentwise method. When inventory costs were taken into account, the compartmentwise method was still the most efficient inventory method in the study area. Forest inventories, however, are usually directed to larger areas when the costs per hectare of remote-sensing methods decrease. As a result of better accuracies, 3D and compartmentwise methods always produce better results than the 2D method when NPV losses are accounted. Simulations of this type are based on the accuracies and costs of the 3D data available today, assuming that the data can be used in tree-level measurements.

Keywords forest inventory, laser scanning, digital aerial photographs, digital photogrammetry, net present value, expected net present value loss
Authors' address University of Helsinki, Department of Forest Resource Management, P.O. Box 27, FI-00014 University of Helsinki, Finland **E-mail** markus.holopainen@helsinki.fi
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1 Introduction

Compartmentwise forest inventory is a widely used method in Finland, both in public and privately owned forests. The basic unit of forest inventories is a forest stand, which is used as the management-planning unit. The size of a forest stand is normally 0.5–2 ha. The forest stand is defined as a homogenous area according to relevant stand characteristics, e.g. site fertility, composition of tree species and stand age. Forest inventory data are mostly collected with the aid of field surveys, which are both expensive and time-consuming. The method is also sensitive to subjective measurement errors. Remote sensing is normally used for nothing more than delineation of compartment boundaries. The total costs of compartmentwise inventory in Finland were 17.9 €/ha in 2000, of which 7.9 €/ha, i.e. 45% of the costs, consisted of field measurements (Uuttera et al. 2002).

Two of the most promising new remote-sensing technologies for increasing the accuracy and efficiency of forest inventories are treewise or standwise measurements of airborne laser scanner data or digital aerial photographs. The present state of the art of these technologies indicates a high potential for assessing various parameters of single trees, forest plots and stands (e.g. Næsset 1997a,b, 2003, 2004, Nilsson et al. 2003, Wulder 2003, Hyyppä et al. 2004).

Individual trees can be measured with the aid of 2-dimensional (2D) data obtained from single digital aerial photographs or 3-dimensional (3D) data obtained from either several aerial photographs or airborne laser scanning. In tree-level analyses tree crowns and tree species can be measured with 2D or 3D data, heights of the trees only with 3D data. Other forest characteristics, e.g. tree diameter at breast height (dbh) or tree volume, are derived by means of allometric models in which independent variables (tree species, tree height and tree crown area) are measured (Korpela 2004, Kalliovirta and Tokola 2005). Successful implementation of this approach requires successful tree crown identification, especially in two-storey and multistorey stands, and appropriate tree models. Theoretical models taking into account trees invisible in the remotely sensed imagery are also required.

Laser scanning provides 3D information on the object. Recent developments in laser scanners, global positioning systems (GPS) and laser techniques have made the development of laser scanning in forest planning possible. A laser scanner emits an optical/infrared laser pulse perpendicular to the flight path. Each image row consists of pixels representing nearly adjacent ground elements. The x, y and z coordinates are derived for each pixel. By analysing these measurements both 3D terrain and crown models can be derived. The difference in these models is the height model of the stock. The main advantage of this technology compared with optical remote sensing is that in this case the physical dimensions of the imaged objects are measured directly. Ground-referenced measurements are therefore not required, which in turn reduces the total measuring costs (Hyyppä and Inkinen 1999).

Applications of airborne laser scanning in forestry include determination of terrain elevations (e.g. Kraus and Pfeifer 1998), standwise mean height and volume estimations (e.g. Næsset 1997a,b), individual tree-based height determination and volume estimation (Hyyppä and Inkinen 1999, Brandtberg 1999), tree species classification (e.g. Brandtberg et al. 2003, Holmgren and Persson 2004), and measurement of forest growth and detection of harvested trees (Yu et al. 2004). The accuracies of laser-scanning estimates at the tree, plot and stand levels are very similar to or even better than those achieved in traditional field inventories (Holmgren 2003, Næsset 2004).

Extraction of forest variables using laser scanner data has been divided into 2 categories: inventories done at the stand and plot levels and individual tree-based inventories. From the methodological point of view, methods can be divided into statistical and image processing-based retrieval methods (Hyyppä et al. 2004).

In the statistical methods, features and predictors are assessed from the laser-derived surface models and point clouds, which are used for forest parameter estimation, typically employing regression analysis. The height percentiles of the distribution of canopy heights were used as predictors in regression models for estimation of mean tree height, basal area and volume (Lefsky et al. 1999, Magnussen et al. 1999, Means et al. 1999, Næsset 1997a, b, 2002, Næsset and Økland 2002).

Physical features such as crowns, individual trees, groups of trees or whole stands can be delineated, using image-processing techniques of laser scanner data (Hyyppä et al. 2004). Finding tree locations can be done by detecting local image maxima. In laser scanning, local maxima are detected with the canopy height model. After finding the local maxima, the edge of the crown can be found with the processed canopy height model. This approach can provide tree counts, tree species, crown area, canopy closure, gap analysis and volume and biomass estimation (Gougeon and Leckie 2003).

Hyyppä and Inkinen (1999) were the first to demonstrate a tree-based forest inventory using a laser scanner to find maximal values with the canopy height model and segmentation for edge detection. In coniferous forests 40–50% of the tree could be correctly segmented. Persson et al. (2002) improved crown delineation and could link 71% of the tree heights with the reference trees. Other attempts at using the tree-based approach were reported by Brandtberg et al. (2003), Leckie et al. (2003) and Popescu et al. (2003). However, methods for tree based measurements using laser scanner data are still under development and empirical studies on the quality of the approaches are needed.

Aerial photos have traditionally been used in forest management planning. As a result of technological advances, the interpretation of aerial photos has evolved from analogue imagery and devices to digital applications. An analogue aerial photo can be digitized by scanning or the photos can be taken directly with digital cameras. Numerical aerial photos can be rectified to a desired coordinate system. The effects of terrain elevation can be considered with a digital elevation model. The result of such rectification, an orthophoto, is spatially almost as accurate as a common map. In addition, the image is highly scalable. Digital orthophotos are currently used commonly as background images in forestry mapping and geographic information system (GIS) applications (Holopainen 1998).

There are several 2D approaches for interpreting tree crowns in single digital aerial photographs. A crown model can be derived and corresponding crowns in the image can be sought. Problems stem, however, from the fact that crown images vary greatly, depending on crown illumination and location in the image. Another alternative is to analyse the image statistically to identify pixel sets having high grey tones and to assume they depict actual tree crowns. This approach is in turn highly dependent on the imaging scale used and the conditions encountered. The image can also be statistically divided into segments representing crowns and noncrowns. Furthermore, borders between illuminated crowns and intermediate areas can be sought. Finally, combinations of these approaches can be used (Holopainen et al. 2000, Anttila and Lehikoinen 2002).

Korpela (2004) presented a new forest inventory method in which multiple digital aerial photographs are used for manual and semiautomatic 3D positioning of treetops, species classification and measurements of tree height and crown width. Tree height and volume can be measured at the same accuracy as by laser scanning. Tree species can be determined to about 80–90% correctness (Korpela 2004). It is possible to achieve better accuracies when 3D digital photogrammetry is used than with an inventory method based on 2D measurements of digital aerial photographs (Uuttera et al. 2002, Korpela 2004, Korpela and Tokola 2006). Korpela and Tokola (2006) examined the differences in 2D and 3D aerial photographic estimations and indicated that the 2D scheme is more prone to systematic errors in mean crown diameter and mean diameters of trees. In comparison to field measurements in which the measuring pace is 15–20 trees per hour, with the 3D method it is possible to measure 40–80 trees per hour if all trees are measured manually.

The new remote-sensing techniques are, however, expensive. The costs of aerial laser-scanning data acquisition are dependent on the size of the survey area. On the other hand, costs are always decreasing due to improvements in availability of laser scanners and technological development. If it is possible to achieve more exact management chains with the aid of accurate and updated information, the new remote-sensing techniques will be promising alternatives to forest inventories.

Reliable inventory data are essential for forest planning. Usually, future expectations focus only on the state of harvesting costs and timber prices and less on the losses caused by incorrect estimation of stand variables. In assessing the state of a stand the estimates may differ significantly from the real situation, due to the inventory method used.

Few studies have compared the various inventory methods from an economic point of view. Holmström et al. (2003) examined the usefulness of k-nearest neighbour (kNN) -assigned reference sample plot data for forest management planning, using cost-plus-loss analyses. They determined that the costs could be decreased by 15–50% if the inventory method were chosen separately in each stand according to the lowest cost-plus-loss of the method instead of using the best method for determining the average for the entire estate. It was, however, difficult to decide which method should be used when the general stand descriptions were known. Eid (2000) examined the impact of erroneous initial description of forest stand variables in long-term timber production analyses using net present value (NPV) losses. He discovered that the largest losses appeared in stands that approached their optimal economical rotation ages. Eid et al. (2004) compared the visual stereoscopic photointerpretation and laser scanning-based inventories of basal area, dominant height and number of trees per hectare by means of cost-plus-loss analyses. Statistical standwise methods were utilized in laser scanning. Only the inventory costs of laser scanning proved to be more expensive than those of photointerpretation, but as a result, the NPV losses and total costs of laser scanning were considerably smaller.

The expected NPV is one of the most common profitability criteria used in forest planning and is a powerful tool in valuing forest properties (Klemperer 1996). The NPV is described as the present value of revenues subtracted from the present value of costs. If the NPV is positive, the investment is profitable with the discount rate used. In forest planning, 3% and 5% discount rates are normally used for profitability calculations. The discount rate describes the decisionmaker's return and profitability requirements for expected net income (Ahonen 1970). The degree of discount rate is dependent on the alternative investments and the decisionmaker's priorities.

The aim of the present study was to compare the traditional compartmentwise forest inventory method with individual tree-based 2D and 3D measurements of digital aerial photographs and airborne laser scanning. Comparison was based on the expected NPV losses, which consisted of the inventory costs and incorrect timings of treatments. The reference data consisted of standwise information measured from the study area.

2 Material

The study region (Fig. 1) is located in southern Finland; the area is part of the forests of the Helsinki City area called Central Park. Central Park is a recreational area of Helsinki whose forests are managed to preserve biodiversity despite the presence of environmental stress and heavy recreational use. The area is 700 ha, of which the forested area comprises 680 ha. It does not consist entirely of typical boreal forest due to its age and site structure, which are older and better, respectively, than that found in typical forests in Finland (Finnish Statistical Yearbook of Forestry, 2004). The forest of the area is predominantly

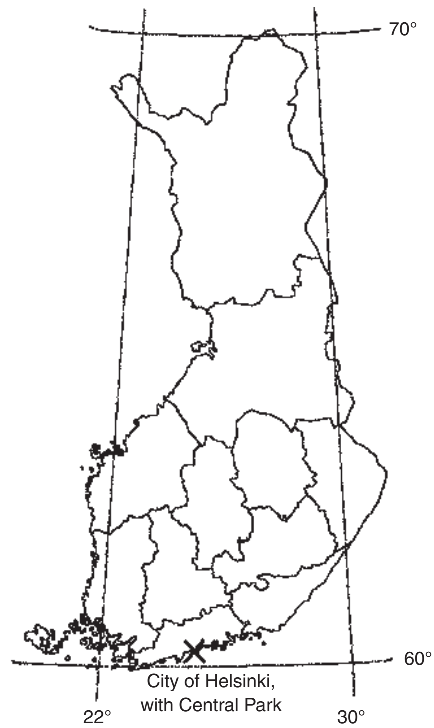

Fig. 1. Location of the study area.

Table 1. Distribution of field data into site classes and main species (per hectare). Percentages in parentheses.

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. Mean values and standard deviations (SD) of the data. H = mean height (m), $D_{1.3}$ = mean diameter (cm), G = basal area (m^2/ha), N = number of stems (n/ha), V = stand volume (m^3/ha).

Variable	Mean	SD
H	18.6	7.4
$D_{1.3}$	25.1	10.8
G	20.2	11.7
N	1156	1593
V	175.8	95.7

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 1). For the purposes of the study, all deciduous tree species are treated as silver birch (*Betula pendula* Roth), which covers a total of one fourth of the study area. The third main tree species is Scots pine (*Pinus sylvestris* L.).

The descriptive statistics of the data is represented in Table 2. The mean volume was 175.8 m^3 ha^{-1} and mean basal area 20.2 m^2/ha. The mean height was 18.6 m with standard error of 7.4 m, mean diameter was 25.1 cm and mean number of stems per hectare was 1156. The mean age of the stands was 68 years when the oldest stands were 127 years. Most of the study area comprises mature stands, and the proportions of seedling and young stands are small (Table 3).

The data consisted of compartmentwise information of the area. The stand variables used in the study were forest site type, main tree species, stem number per hectare, stand age at breast height, mean diameter and mean height.

3 Methods

Laser scanning or digital aerial photographs can be used in forest inventory either at the stand level, using a statistical modelling -based approach, or at the tree-level, using an image processing -based approach. These methods are called here the stand-wise and tree-wise methods. Furthermore, the treewise method can be divided into 2D and 3D methods, depending on the remote-sensing material used. In our simulation the accuracies and costs are based on the treewise 2D and 3D methods. For comparison, the accuracies and costs of traditional compartmentwise inventory, which is based mainly on field measurements, are used and called compartmentwise method.

3.1 Accuracy of Data Acquisition

Extensive research in Finland has been undertaken on the accuracies of traditional compartmentwise forest inventory methods (e.g. Poso 1983, 1994, Koivuniemi 2003). The figures shown in Table 4 are mean values of the wide range of estimates obtained using the compartmentwise method. The accuracies can be achieved in stands that are in the developmental phase between young and mature (Uuttera et al. 2002).

Table 3. 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 satisfied the criteria for maturity depending on species and site index), 05 = shelterwood stand, Y1 = seedling stands with holdover trees, S0 = stands in seed-tree position.

Development 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

The accuracy of standwise or treewise 3D measurements of digital aerial photographs and laser scanning was evaluated in several recent studies (Holmgren 2003, Korpela 2004, Næsset 2004, Hyyppä and Hyyppä 2003). Hyyppä and Hyyppä (2003) and Korpela (2004) evaluated the treewise 3D method accuracies that were used in the present study (Table 4). The differences between the accuracy of laser scanning and of digital aerial photographs are slight and, therefore, we combined the methods for simulations. These methods are here referred to as 3D methods in the methods and results section.

3.2 Cost of Data Acquisition

The current costs of 3D data acquisition using 1:16 000 and 1:6 000 digital aerial photographs or laser scanning (5 pulses/m^2) in larger areas are about 0.5–1€/ha, 2.5–3 €/ha or 3.5–4 €/ha, respectively, depending on the remote-sensing material and the size of the area (Fig. 2), while postprocessing costs are 4–6 €/ha. Thus, the inventory costs of 1:16 000 and 1:6 000 digital aerial photographs vary between 2.4–6 €/ha and 6.5–10 €/ha, respectively. In addition, field measurements would still be needed, i.e. the costs of 3D methods are probably equal to or larger than the costs of field measurements in compartmentwise inventory (7.9 €/ha) at any size of the area when using 1:6000 aerial photographs or laser scanning data are used. With smaller-scale aerial photographs, it would be possible to achieve lower costs; however, the data are more inaccurate. The inventory costs used in this study were based on data acquisition obtained in several research areas of the University of Helsinki and the Finnish Geodetic Institute. We assume the costs reflect the true market costs and treewise approach as used in the inventory. If statistical standwise measurements or interpretation are used, the costs would be lower due to higher flight altitude in laser scanning or aerial photography.

The data were simulated to final cut with the MOTTI simulator. The MOTTI is a stand-level analysis tool that can be used to assess the effects of alternative forest management practices on growth and timber yield (Salminen et al. 2005). The data required for input to the MOTTI simulator are designed to include the variables usually presented in forest planning (Hynynen et

Table 4. Accuracies (RMSE%) of different inventory methods (Hyyppä and Inkinen 1999, Uuttera et al. 2002, Korpela 2004, Næsset 2004). d_{gM} = diameter of the basal area median thee. h_{gM} = height of the basal area median tree.

	3D and laser scanning			Compartmentwise inventory			2D photographs		
	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

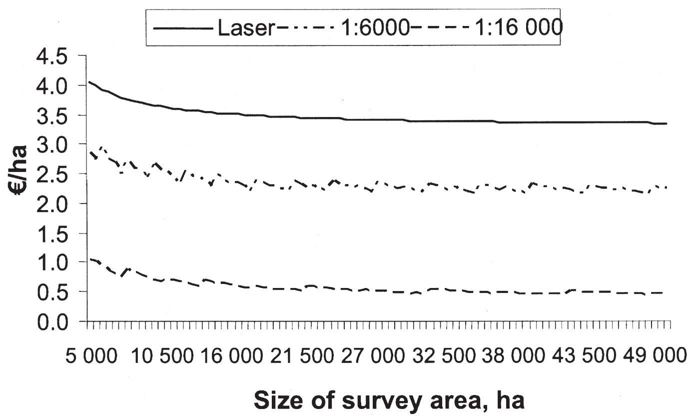

Fig. 2. Inventory costs of laser scanner and two different scales (1:6000, 1:16000) of aerial photographs as a function of the survey area.

Table 5. Prices of wood (€/ha) assortments by species in the Helsinki region in 2003.

	Log	Pulp
Pine	44.6	12.8
Spruce	43.9	21.8
Birch	41.0	11.9

al. 2005). The variables needed for the MOTTI concern the location, site and treatment history of a stand. In addition to general stand information, the simulator also requires either tree- or stand-level information on the growing stock (Hynynen et al. 2005). The static models of the simulator update the tree and stand characteristics (e.g. tree and stand volumes) during the simulation, while the dynamic models are applied to predict tree growth and mortality rates for 5-year periods (Hynynen et al. 2002). It is possible to simulate harvests of a stand in several ways; thus, a user can define the treatment options.

Hynynen et al. (2005) used the MOTTI simulator in analysing the effects of different forest management schedules on stand development. The growth and yield models applied within the MOTTI are described in detail in Hynynen et al. (2002). For more technical information on the MOTTI simulator, see Salminen et al. (2005).

The definitions of final cut for the various main species and forest sites were those of the Tapio Forestry Development Centre, which are generally used in Finland (Oksanen-Peltola et al. 1997). The costs of thinning were 12.46 €/m^3 and final cut 6.95 €/m^3 in Finland in 2002 (Örn 2002), and the prices of logs and pulpwood are those for the Helsinki region in 2003 (Table 5).

The stands were classified by main tree species, developmental class and site index. There were in all 63 classes; however, the seed-tree position, shelterwood, hold-over-tree and seedling classes were not used in the simulations. Thus, a total of 40 classes were selected for the study.

The stand variables (stems per hectare, age, diameter and height) of class i were calculated to obtain the average for all the stands in class i, which constituted the reference data. The accuracies of compartmentwise, 2D and 3D measurements of digital aerial photographs and laser scanning inventories (Table 4) were used for calculating the upper and lower limits for each inventory method in class i. The proportions shown in Table 4 are added to or reduced from the reference data values. However, only the lower limit of stems per hectare was used for both 2D and 3D measurement methods since the estimate for the variable is in all cases underestimated, due to the low discernibility rate of suppressed trees (e.g. Maltamo et al. 2004, Korpela 2004). For these inventory methods, the upper limit of stems per hectare was the reference data value.

With the 2D and 3D methods, we assumed that the site classes, main species and developmental classes were known. All deciduous tree species were treated as birch.

Each class in the reference data was first simulated to final cut, according to the harvesting definitions used in Finland. Secondly, the calculated upper and lower limits for each class and inventory method were also simulated. Logically, the differences in simulated harvest timings between the reference data and the calculated data of the compartment-wise, 2D and 3D inventory methods in class *i* are due to the inventory accuracies. With the harvest timings of each inventory method in the second phase, the reference data were simulated again. In this way, the consequences of not selecting optimal harvest timing were seen. The upper and lower limits of each inventory method were combined in the results, since in reality it is not possible to know if the accuracy precision is under- or overestimated.

In the present study, discount rates of 3% and 5% were selected; the range is relevant for most forest owners (Hyytiäinen and Tahvonen 2001). The acquisition accuracies were analysed with the NPV, which is defined as the discounted value of future harvesting incomes. The standard investment formula for a timber stand (cf. Raunikar et al. 2000) with some modifications was used:

$$\mathrm{NPV} = \sum_{i}^{\mathrm{I}} \frac{H_i}{(1+r)^i} + \frac{V_t}{(1+r)^t} \tag{1}$$

where i = the time to thinnings, H_i = the commercial value of thinning removal minus harvesting cost at year i (€ ha^{-1}), V_t = the commercial value of the stocking at the final cut minus felling cost (€ ha^{-1}), t = the time to final cut and r = the discount rate. The land value was excluded from the calculations. The final cut and harvest returns occur in the future and, therefore, they must be discounted. Thus, the NPV is here the discounted value of future returns.

When the expected NPVs of alternative investments are compared, it is possible to find the most suitable object in which to invest. In forestry, alternative inventory methods can be compared, using the expected NPV as the criterion for choosing the most profitable method. In the present study, the differences in yield between the alternative inventory methods and reference data were analysed using expected NPV losses. The expected NPV loss describes how much the NPV of a given inventory method differs from that of the reference data. The more positive the NPV loss, the greater is the loss of a given inventory method. The expected NPV loss per hectare in class i with inventory method j was calculated as

$$\mathrm{NPVloss}_{ij} = \mathrm{NPV}_{\mathrm{reference}i} - \mathrm{NPV}_{\mathrm{invmethod}ij} \tag{2}$$

For the entire study area, the NPV loss per hectare for inventory method j (Eid et al. 2004) was calculated as

$$\mathrm{NPVloss}_j = \frac{1}{n}\sum_{i=1}^{n} \mathrm{NPVloss}_{ij} \tag{3}$$

The mean value of the expected NPV losses from the upper and lower limits was used to compare the inventory methods.

4 Results

For all the reference data, the expected NPVs using 3% and 5% discount rates were 8880 €/ha and 8473 €/ha, respectively. The discounted values did not vary widely, since most of the classes were mature (Table 3) and designated for clearcutting in the first 5-year period. Only a small proportion (less than 10%) of young stand classes needed simulation several 5-year periods before clearcutting.

When inventory costs were not considered, the

Table 6. Expected NPV losses per hectare of different inventory methods in the area studied, without and with inventory costs. Discount rates 3% and 5%.

	Without inventory costs		With inventory costs	
	3%	5%	3%	5%
Compartmentwise	375	490	383	498
2D measurements	1014	1372	1022	1380
3D measurements	387	512	400	525
Laser scanning	387	512	405	530

Table 7. Expected NPV losses in development classes by species.

Development class	Species	3D		Compartmentwise		2D	
		3%	5%	3%	5%	3%	5%
02	Pine	71	54	71	35	150	114
02	Spruce	801	646	792	638	1076	826
02	Birch	121	60	73	21	–506	–353
03	Pine	–235	–247	–237	–195	387	603
03	Spruce	1449	1176	1255	1012	1786	1573
03	Birch	–812	–410	–350	–27	–356	2
04	Pine	637	916	471	683	450	640
04	Spruce	17	28	12	20	1242	1727
04	Birch	1436	2091	1428	2068	2323	3268

expected NPV losses of the 3D methods with 3% and 5% discount rates were 387 €/ha and 512 €/ha, respectively (Table 6). The expected NPV loss is the difference between the reference data and an inventory method. The compartmentwise method showed slightly smaller NPV losses than the 3D methods, while the 2D method showed the largest NPV losses. When the NPV losses are accounted for, the 3D and compartmentwise methods always produce better results than the 2D method, due to their greater accuracies.

In addition, compartmentwise inventory proved to be the most efficient inventory method when inventory costs were taken into account (Table 6). However, forest inventories are usually directed to large areas when the costs per hectare of remote-sensing methods decrease. The 3D data would cost approximately 10–12 €/ha if the inventory were carried out only in the study area.

The most extensive NPV losses were in the middle-aged spruce class and the mature birch class The expected NPV losses according to the development class and tree species are seen in Table 7. If the NPV loss is negative, the treatment timings for a given inventory method would lead to more cost-efficient solutions than were shown in the reference data. This was the case in middle-aged pine and birch stands when 3D or compartmentwise inventory methods were used. Moreover, with the 2D method the expected NPV losses were negative or only slightly positive for young and middle-aged birch stands.

The number of thinnings was the same, regardless of the inventory method used. As expected, the thinnings and final cut were carried out earlier when the upper accuracy limit was used, i.e. the values were overestimated, and vice versa.

However, the expected NPV values of the overestimated stand data for all inventory methods were in most stands greater than those of the reference data. This was due to the degree of discount rate; from an economical point of view, the larger the degree of rate, the sooner that final felling should be carried out.

5 Discussion

Compartmentwise inventory showed the smallest NPV losses of all inventory methods. However, the area studied was small (700 ha) and therefore the acquisition costs of the remote-sensing techniques per hectare were significant. Normally, inventories are focused on larger (over 10 km^2) areas that decrease the costs per hectare of remote-sensing material and photointerpretation. When the 2D method is used, the costs per hectare decrease with respect to the size of the area. However, in accounting for NPV losses the 3D and compartmentwise methods always produce better results than the 2D method, due to their greater accuracies.

The discount rate chosen for the calculations is often a crucial variable in considering the result. If a higher discount rate is chosen, the future outcome is smaller if the investment period is constant. The individuality of the chosen discount rate is based widely on the fact that in decision-making there is always a question of both a person's relationship to his or her economic field and its economic variables. Moreover, the question is also about the relationship of a person's decision compared with other economic decisions and how a person takes them into account (Ahonen 1970).

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

The MOTTI simulator is designed to be applied to growth prediction for all the major tree species and sites throughout Finland (Hynynen et al. 2002, 2005). Without calibrating the models, MOTTI is reliable only in Finland or conditions similar to those encountered in Finland. However, the models are always generalizations and are therefore prone to inaccuracies and biases. The inaccuracies in the simulations could not be calculated in this study, but affected the results.

The results of this study are based directly on the accuracies used (Table 4). Since the interest here was in the NPV losses of different forest inventory methods, it did not matter that the actual conditions in the stands most likely differed to some extent from those of the reference data. The main species and site recognition were assumed to succeed with 100% 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) and 95% (for coniferous trees, Holmgren and Persson 2004), respectively. Incorrect species recognition results in random effects in diameter and volume estimations. Moreover, the accuracy in species recognition needs to be over 85% so that the errors caused by averaging would not be significant (Korpela and Tokola 2006). Correct species recognition is required if aiming for accurate estimates e.g. in timber assortments, since growth models and calculation of timber volumes are usually species-dependent. Thus, species recognition will become one of the most important future research areas in treewise 3D measurements.

The usability of remote sensing-based forest inventory in practise is dependent on the amount of fieldwork needed. Assuming the accuracy of 3D data in estimating forest variables such as tree height, 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, it would be possible to estimate the volume of the stand, tree species and timber assortment distributions without field measurements. In addition, it would be possible to measure the growth of the trees and site quality using multitemporal laser-scanning data. However, field measurements would still be needed in data calibration, determination of stand treatments and in assessment of biodiversity indicators or key biotopes.

The costs and accuracies of different inventory methods show that compartment-wise inventory would be the most cost-efficient method at any size of inventory area. The simulations of this study were based on the accuracies and costs of the 3D data available today, assuming that the data can be used in tree-level measurements (scale of digital aerial photographs larger than 1:16 000, with at least five laser pulses/m^2). However, it should be possible to later achieve more accurate 3D data at similar or lower costs than are available today.

In addition to the size of the study area, the costs of digital aerial photographs are dependent on the overlap and scale of the photographs. The costs will increase significantly if more photographs are taken from the area for 3D measurements. The costs of laser scanning are dependent on the flight altitude, size and shape of the test area. The total information in the data is dependent on the number of laser beams per hectare; lower flight altitudes produce more detailed information from the area than is available at higher altitudes, but are also more expensive.

Here, accuracies and costs of the laser scanning and aerial photography were based on treewise approach. Further studies would be needed for comparing the NPVs of treewise approach with statistical standwise forest inventory methods.

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