Effect of airborne laser scanning accuracy on forest stock and yield estimates

Markus Holopainen

Aalto University

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Effect of airborne laser scanning accuracy on forest stock and yield estimates

Markus Holopainen

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Abstract

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Abstract

The main objective of the study was to assess the magnitude of uncertainty of airborne laser scanning (ALS) -based forest inventory data in forest net present value (NPV) computations. A starting point was the current state of change in operative forest-planning in which traditional standwise field inventories (SWFI) are being replaced by area-based ALS inventories (A_ALS). The more detailed objectives were as follows: 1) to investigate the significance of the accuracy of current (SWFI, A_ALS) and future (ALS individual tree detection (ITD)) forest inventory methodologies applied in the timing of simulated loggings and in NPV computations, 2) to compare the forest-planning inventory methods currently applied with respect to the accuracy of the timber assortment information derived, 3) to investigate the sources of uncertainty related to the estimation of timber assortment volumes and economic values in forest management-planning simulations and 4) to compare the uncertainty related to inventory accuracy, growth models and timber price development in NPV computations at the stand- and forest property-level, using various interest rates. The study was carried out, using empirical and simulated forest inventory data, forest management-planning calculations and Monte Carlo simulations.

It was shown that forest inventory errors led to significant mistiming of simulated loggings and subsequent prominent losses in simulated NPV. The most significant source of error in the prediction of timber assortment outturns was SWFI and A_ALS inventory error. The errors related to stem distribution generation, stem form prediction and bucking simulation were significant but considerably lower in magnitude than the inventory error. A_ALS interpretation led to accuracy levels similar to or better than that of SWFI. At the stand-level the growth models used in forest-planning simulation computations were the greatest source of uncertainty with respect to NPVs computed throughout the rotation period. Uncertainty almost as great was caused by A_ALS and SWFI data uncertainty, while the uncertainty caused by fluctuation in timber prices was considerably lower in magnitude. Forest property level deals with a considerably lesser degree of NPV deviation than does stand-level: A_ALS inventory errors were the most prominent source of uncertainty, leading to a 5.1-7.5% relative deviation in property-level NPV when an interest rate of 3% was applied. A_ALS inventory error-related uncertainty resulted in significant bias in property-level NPV estimates. The study forms a basis for developing practical methodologies for taking uncertainty into account in forest property valuation.

Keywords Forest property valuation, Net Present Value, forest management planning, forest inventory, Airborne laser scanning, Monte Carlo simulation

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Tiivistelmä

Väitöskirjan päätavoitteena oli tutkia lentokonelaserkeilaukseen (airborne laser scanning, ALS) perustuvan metsien inventoinnin epävarmuutta metsätaloudellisen tuottoarvon (nettonykyarvo, net present value, NPV) laskennassa. Tutkimuksen lähtökohtana oli parhaillaan menossa oleva operatiivisen metsäsuunnittelun muutos, jossa kuvioittaiseen arviointiin perustuva inventointimenetelmä ollaan korvaamassa laserkeilausmenetelmällä. Yksityiskohtaiset tavoitteet olivat seuraavat: 1) Tutkia metsäsuunnittelussa käytettävissä olevien metsävarojen inventointimenetelmien (kuvioittainen arviointi, aluepohjainen ALS-inventointi, ALS-yksinpuintulkinta) tarkkuuden merkitystä hakkuiden ajoituksessa sekä NPV:n laskennassa. 2) Vertailla metsäsuunnittelun inventointimenetelmien tarkkuutta puutavaralajitason tiedon tuottamisessa. 3) Tarkastella puutavaralajien määrän ja taloudellisen arvon estimointiin liittyviä epävarmuuden lähteitä. 4) Vertailla inventointitiedon tarkkuuteen, kasvumallien toimintaan ja raakapuun hintakehitykseen liittyviä epävarmuustekijöitä NPV:n laskennassa kuvio- ja tilatasolla. Tutkimuksessa käytettiin empiirisiä ja simuloituja metsävara-aineistoja. Tutkimusmenetelminä olivat empiirinen mallinnus, metsäsuunnitteluun liittyvät laskennat sekä Monte Carlo -simuloinnit.

Tutkimus osoitti, että metsävarojen inventointiin liittyvät virheet johtivat merkittäviin hakkuiden ajoituksen virheisiin ja simuloitujen NPV-arvojen menetyksiin. Puutavaralajien estimoinnin merkittävin virhelähde oli kuvioittaiseen arviointiin tai aluepohjaiseen ALS-inventointiin liittyvä virhe. Runkolukusarjan ja puun runkomuodon ennustamiseen sekä katkonnan (apteerauksen) simulointiin liittyvät virheet olivat huomattavasti pienempiä kuin inventointiin liittyvät virheet. Aluepohjainen ALS-inventointi tuotti kaikissa osatutkimuksissa vähintään samaa tai hieman parempaa tarkkuustasoa kuin kuvioittainen arviointi. Kuviotasolla kasvumalleihin, kuvioittaiseen arviointiin ja aluepohjaiseen ALS-inventointiin liittyvät virheet olivat suurimmat epävarmuuden lähteet kiertoajan yli lasketussa metsätaloudellisessa tuottoarvossa. Raakapuun hintakehitykseen liittyvä epävarmuus oli huomattavasti pienempää. Tilatasolla aluepohjaiseen ALS-inventointiin liittyvä virhe oli suurin epävarmuuden lähde, johtaen 5.1-7.5 % suhteelliseen NPV:n hajontaan (korkokanta 3%). Aluepohjainen ALS-inventointi aiheutti merkittävää harhaa tilatason NPV-estimaatteihin. Tutkimus loi perusteita kehittää käytännön menetelmiä metsäomaisuuden arvonmääritykseen liittyvän epävarmuuden huomiointiin.

Avainsanat metsäomaisuuden arvonmääritys, metsätaloudellinen tuottoarvo, nettonykyarvo, metsäsuunnittelu, metsäninventointi, laserkeilaus, kuvioittainen arviointi, Monte Carlo –simulointi

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Fields of responsibilities

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1 Background

The economic value of forests is crucial information for landowners and various forestry organizations. Estimates of the value of forest property are needed for many purposes, e.g. in the real estate business, land divisions and exchanges, and for considering forestry investment. The need to determine the value and the value development of forests has become more important, since forests are increasingly considered as one possible investment outlet amongst other real or financial assets. The International Financial Reporting Standards (IFRS) require that forest enterprises annually present systematically computed estimates of the value of their forested land.

According to the International Valuation Standards (IVS, International Valuation Standard Council 2007), real estate value deals with two basic groups of values: market-based values and other than market-based values. The most common type of value related to property valuation is market value, which depicts the common expectations and functionality of markets. Market-based valuation methodologies include the sales comparison, income and cost approaches (Lusht 1997, International Valuation Standard Council 2007). The above-mentioned approaches and applications related to them are commonly used in real property valuation. In determining the market value of a given property, the factors required by the various approaches should be derived from the markets. Thus, all approaches can be considered as comparative methods. The same valuation methodologies can be applied to determine other than market-based values, but they are usually related to purposes other than achieving market value (International Valuation Standard Council 2007).

In the sales comparison approach the target's market value is derived by comparing the target to recently realized transactions resembling the target as much as possible. In Finland, the purchase price register (PPR) has been recorded since 1983 by the National Land Survey of Finland (NLS) (Airaksinen 2008). Unfortunately, in the case of forest properties, the representativeness of the PPR is rather poor, because it is difficult to find similar forest transactions in a given area and time span. In fact, there are no two completely identical forest stands or properties. A far greater problem related to the possible utilization of this approach is, however, the total lack of stock and site productivity information on the PPR, which, on the other hand, almost totally dictates the forest property's value.

In Finland, the primary method used for determining forest market value is the summation approach in which the value of a forest property is derived as the sum of its land value and the stock's present and future expected values (Paananen et al. 2009). The method's advantages with respect to the alternative sales comparison and income approaches are its simplicity and the fact that the bare land and expected stock values required by the method are in Finland comprehensively tabulated. Its most significant drawback has been the vaguely defined correction coefficient of the total value, which has been recommended, depending on source and case, to lie in the range of 40-85% of the sum of the land and stock values (Forestry Development Centre Tapio 1997, 2002, Hannelius & Airaksinen, 2005, Airaksinen 2008). In practice, the coefficient is determined subjectively, based on the experience of the assessor.

The traditional method of deriving the economic value of a forest stand or property is to calculate the difference between the present values (net present value, NPV) of all future expected revenues and expenses. Here, this approach is referred to as the forestry yield value method (Holopainen & Viitanen 2009) and it is based on the fundamental ideas of forest economics (Faustmann 1849). The estimation of future chains of forest stand management and the flow of revenues and expenses are most commonly performed on the basis of the harvest and silviculture recommendations presented in the respective forest management plan. Revenues and expenses are estimated based on the wood production predictions that are commonly determined by simulation and optimization computations carried out by specific forest-planning software systems.

Decisive issues regarding the determination of forestry yield value include determination of the optimal rotation length, the timing and intensity of harvests, timber stump prices, silvicultural costs and the applied interest rate. The NPV of forested land is subject to various uncertainties. These include errors in the forest inventory data, growth and yield models used in the simulators, development of timber prices and the rate of interest.

The starting point for valuating forest property must always be forest inventory data describing the property's wood resources, sites and possible other than wood production-related values. The accuracy of this information is strongly dependent on the inventory methodology used. Forest-planning simulations are based on a vast number of models depicting the development of single trees or forest stands (in Finland, 400-600 models depending on the forest-planning software system). These models are never complete, notwithstanding the manner in which they were derived. The complexity of the problem is further heightened by the fact that uncertainty factors tend to accumulate due to the long chains of models and long observation periods used. If the computation input data are inaccurate, they will significantly affect the functionality of the simulation models, resulting in unrealistic simulation outputs and correspondingly wrong optimization solutions.

Acquisition of forest-planning data is currently in a phase of radical change. In Finland, operative forest planning is evolving into a methodology through which stock characteristics are estimated by means of tree-wise measured sample plots and area-based statistical features of airborne laser scanning (ALS) data and digital aerial photographs. Estimation will be performed, using the nonparametric k-nearest neighbour (k-NN) or k-most similar neighbour (k-MSN) method (Packalén & Maltamo 2007). At present, the crucial question remains about how to integrate this new inventory data into forest-planning computations. It is then essential to be aware of how stock data obtained at various accuracy and scale levels affect simulation end results, i.e. timing of simulated loggings and calculation of forestry yield value, which have a significant influence on the forest owner's finances.

2 Starting points and objectives of the study

2.1 Starting points

The starting point of the study was the assumption that regardless of the approach used to determine forest property value, the end result must always be considered as uncertain. The main sources of uncertainty inherent to the forestry yield approach are 1) the forest resource inventory methodology, 2) simulation methodologies and tree- or stand-level models applied in the simulation computations, 3) fluctuations in timber prices and 4) interest rate of capitalization.

In this study, the main focus was on the uncertainties of inventory methodologies; however, three other uncertainty sources were evaluated as well. Several previous studies have dealt with the effects of uncertainty on the end results of forest-planning computations and the updating of forest resource information (e.g. Ståhl 1994a, Haara & Korhonen 2004a, Haara 2005, Hyvönen 2007). Studies from the standpoint of forest property valuation have also been done (e.g. Pukkala 2005, 2006), but the simultaneous analysis of various sources of uncertainty has proved to be challenging. In other words, although it has been evident that figures describing forest stand- or property-level economic value are merely estimates that contain uncertainty, it has not been possible to provide additional figures describing the degree of uncertainty, such as confidence intervals.

A forest property's income stems from loggings carried out during the rotation period. The determination of the timing and intensity of the loggings and the length of the rotation period thus have a profound impact on the outcome of the forestry yield value computations. The timing of loggings is also related to forest property expenses, which mainly stem from loggings and the silvicultural operations following them.

A crucial starting point in the study was the current state of change in operative forest-planning in which traditional standwise field inventories (SWFI) are being replaced by area-based airborne laser scanning (A_ALS) inventories, or, in the future, ALS individual tree detection (ITD, single tree interpretation) methodology. There are several operational methods for forest property valuation, but actually all of these have major problems which is probably why forest property valuation has no international (or national) standards (see International Valuation Standard Council 2007).

When new ALS-based forest management planning is in the operational stage (in Finland 2010) it will open new possibilities for forest valuation. However, it is important to know what the error sources and uncertainties in forest valuation are when carrying it out through forest management planning simulations.

2.2 Objectives

The main objective of the study was to assess the magnitude of uncertainty of airborne laser scanning (ALS) based forest inventory data in forest net present value (NPV) computations. A starting point was the state of change currently present in operative forest-planning in which traditional standwise field inventories (SWFI) are being replaced by area-based airborne laser scanning (A_ALS) based inventories. The more detailed objectives were as follows: 1) to investigate the significance of the accuracy of current (SWFI, A_ALS) and future (ALS ITD) forest inventory methodologies applied in the timing of simulated loggings and in NPV computations, 2) to compare the forest-planning inventory methods currently applied with respect to the accuracy of the timber assortment information derived, 3) to investigate the sources of uncertainty related to the estimation of timber assortment volumes and economic values in forest management planning simulations, and 4) to compare the uncertainty related to inventory accuracy, growth models and timber price development in NPV computations and to determine the joint influence of these three factors at stand- and forest property-level, using various interest rates.

The assumptions applied and the viewpoints excluded from the study were as follows: 1) Only economic values of timber production / forest property value were considered. 2) Energy wood was not considered as timber assortment. 3) Uncertainty of silvicultural cost development was not taken into account in the forestry yield value (NPV) computations. 4) The future demand for timber was assumed to remain unchanged. 5) Future price ratios between various timber assortments were assumed to remain unchanged.

3 Theoretical background

3.1 Uncertainty of forest inventory data

3.1.1 Forest inventory error sources

Forest inventory data accuracy has a decisive impact on the success of forest-planning computations and determination of forest NPV. Errors in inaccurate inventory data increase in magnitude during the execution of long model chains and causes significant output errors, e.g. when updating forest management plans (e.g. Haara 2005, Hyvönen 2007). The longer the reference period, the larger the output errors; thus, inaccurate input data are especially problematic in the case of forestry yield value determination throughout the rotation period. In addition, inaccurate input data cause significant nonoptimal losses in forest planning and forest silviculture if the timing of various treatments fails due to erroneous input data (e.g. Eid et al. 2004, I, II).

Forest inventory error sources consist of measurement, classification, sampling and model errors (Kangas & Kangas 1997). In practice, measurements taken are never completely accurate due to time and cost constraints leading to measurement errors. Measurements can be classified, e.g. into diameter classes that may be more imprecise than the original measurements. Classification errors may also lead to biased end results (Päivinen et al. 1992). Sampling errors occur when the sample does not fully represent the sampled population. The magnitude of the sampling error is dependent on sample size, plot (sample unit) size and sampling method.

Data required for forest property valuation purposes are mainly obtained from forest-planning or separate standwise inventories. Other alternatives for obtaining required input data include measurement of standing trees, plot sampling, remote sensing and various combinations of remote sensing and field measurements. Rough estate-level data may be obtained by interpreting mid-resolution satellite imagery, but to reach the stand or tree level, field measurements, detailed remote sensing (i.e. photogrammetric interpretation of aerial photography or utilization of laser scanning) or a combination of these two is required. The most accurate remote-sensing methods deal with laser measurements taken in the field, the accuracy of which is equivalent to that of traditional single-tree enumerations (measurement on the stump, Vastaranta et al. 2009b). In addition, measurements taken by logging machines provide information on felled trees.

3.1.2 Measurement on the stump

Measurement on the stump was a procedure commonly used to determine timber quantities in the 1970s. It incorporated money transactions related to both timber trading and logging operations. During the late 1970s, approximately half of the timber utilized by the forest industry in Finland was measured on the stump (Laasasenaho 2001). Measurement on the stump was gradually edged out by logging machine measurement in the late 1980s. Currently, measurement on the stump is mainly used in research or for measuring stand plots utilized as ground calibration or reference data in detailed remote sensing. When forest properties are valuated, measurement on the stump can be used in accurate redemption or partitioning procedures.

The general principles for measurement on the stump were derived from stand plot mensuration. The starting point of the procedure is total tree enumeration, during which the breast-height diameter (DBH) of all plot/stand/cutting site/forest holding trees is registered. The enumerated trees are then sampled to determine those trees assigned for further mesurements. The sample trees are measured for upper diameter (d_6), height and increment, after which the measured data are generalized, e.g. by regression analysis of all enumerated trees. Finally, the stem volume can be estimated for all enumerated trees using stem volume or stem curve models (Laasasenaho 1982).

Stem curve models can also be used to determine saw-wood and pulpwood proportions. The sources of error related to measurement on the stump include tree measurement errors, sample tree sampling errors and stem curve bias at individual cutting sites. The standard error of stem volume at the single-tree level is approximately 4-8% but at the cutting site / stand level considerably lower (Laasasenaho 2001).

From the standpoint of forest property valuation, measurement on the stump would be the ideal method for acquiring initial forest data. Unfortunately, traditional methods for acquiring basic forest data are too time-consuming and costly to be adopted in practical forest mensuration. Laser-based field measurement methods may prove cost-efficient enough to be used in future measurement on the stump of larger forested areas.

3.1.3 Plot sampling

Measurement of all trees on a larger forest property is economically not feasible. Therefore, a representative sample of the total tree population is selected, the objective of which is to obtain reliable estimates for the entire tree population. In the case of large forested areas, sampling is based on plots. The most common sampling method then used is systematic plot sampling. For example, systematic clustered plot sampling is used in the Finnish National Forest Inventory (NFI).

Stratification may also be utilized in sampling and can be performed in a multiphase manner. In multiphase sampling inexpensive auxiliary data, such as data obtained by remote sensing, are used for stratifying the forested area into e.g. development classes. Stratified sampling is then performed to select plots to be measured in the field. Finally, field measurement results are generalized by the stratified auxiliary data to obtain estimates for the entire forested area. Stratification and multi-phasing are used to make sampling more efficient. (Tuominen et al. 2006)

The sources of error related to plot sampling include mensuration and model errors inherent in the measurement of plots and sampling errors. Normally, plot mensuration is based on the enumeration and mapping of single trees, i.e. on the principles of measurement on the stump. Therefore, plot measurement accuracies lie in the same ranges as in measurement on the stump.

Samples do not usually depict the original population perfectly, meaning that sample estimates include sampling errors the magnitude of which is dependent on sample size. Sampling errors may be random or systematic. Random errors are characterized by standard deviation (SD) and their mean value approaches zero as the number of measurements taken increases. The occurrence of systematic error or bias, in turn, implies that the error mean does not approach zero, even in large sample sizes, but is either positive or negative. Sampling accuracy is usually characterized with root-mean-square error (RMSE). Forest inventories strive for unbiased estimators that enable correct estimates, given sufficient sample size. For example, the sampling method applied in the NFI produces an unbiased estimate for the total stem volume of Finland, with a standard error of less than 1%. With decreasing sample size the standard error increases rapidly, thus an NFI based solely on field sampling cannot provide cost- efficiently reliable estimates for smaller areas.

Two distinguished methodologies for combining satellite imagery, digital geographic information and field measurements have been developed for forest inventories in Finland: 1) the nonparametric k-nearest neighbour (k-

NN) multisource methodology used by the NFI for generalizing field sample data to small forested areas (Kilkki & Päivinen 1987, Tokola 1988, 1990, Tomppo 1990a, b, Katila & Tomppo 2001) and 2) the Satellite Imagery in Forest Inventory (SMI) system based on multisource auxiliary data and two-phased sampling with stratification (Poso et al. 1984, 1987, 1990, Wang et al. 1997, Tuominen et al. 2006).

A central idea in both systems is to derive forest resource information for smaller forested areas in a more cost-efficient manner than by using field sampling alone. In the NFI, inventory data measured in the field are generalized to mid-resolution (Landsat Thematic Mapper, TM) satellite imagery pixels using nonparametric k-NN estimation. In the methodology, each satellite image pixel is compared by its feature values (e.g. tone values) with the respective feature values of sample plots measured in the field. Then the information on k (e.g. 5) field sample plots having feature values most resembling those of the pixel being interpreted are assigned to the pixel. The importance of each nearest field sample plot can be controlled by weight coefficients. For the estimates produced by the methodology, apart from the weight coefficients, selection of the number of nearest neighbours and remote-sensing features used in the procedure is crucial. (Tomppo 2006)

As an advantage of the k-NN methodology, it can be pointed out that the values for all characteristics measured in the field (more than 100 in the NFI) can be assigned to the interpreted pixels simultaneously. On the other hand, it must be stated that since the underlying auxiliary data source is midresolution satellite imagery, the accuracy of the interpreted characteristics varies. In practice, estimates obtained by multisource NFI can be considered reliable in forested areas larger than 100 ha (Tokola & Heikkilä 1995). However, at the plot and stand levels the error magnitudes resemble those obtained in the interpretation of midresolution satellite imagery, e.g. for stem volume the standard error exceeds 50% (Hyyppä & Hyyppä 1999, Hyyppä et al. 2000). From the standpoint of forest valuation, information produced by the NFI is therefore not accurate enough, at least not at the stand level.

3.1.4 Standwise field inventory by compartments

The basic unit of forest-planning is the compartment, which is defined as a uniform area that can be distinguished by some criteria from its surroundings (Poso 1983). In forest-planning, compartments are usually delineated into uniform areas by future silvicultural treatments. Other factors taken into account include stand age, tree species proportions and ground vegetation. Future development of remote-sensing techniques will probably lead to a transition to the use of smaller sub-compartments or grid cells, enabling analysis of variation within compartments. Compartment inventories are based on the delineation of compartments by visually interpreting aerial photographs and the measurement of subjectively placed relascope plots in the field. The sources of error related to compartment inventories include delineation of compartments, placing of relascope plots, and relascope plot mensuration and model errors (Saari & Kangas 2005). In this thesis compartment inventories are referred to as SWFI methods.

With respect to mean stem volume, the standard error of SWFI can vary between 16% and 38% (Poso 1983, Laasasenaho & Päivinen 1986, Haara & Korhonen 2004a, Saari & Kangas 2005), while tree species stratumwise standard errors are considerably greater. In a study based on NFI data (Haara & Korhonen 2004a), the standard error of mean stem volume was 24.8% and respective bias 1.6%. The relative standard errors at the compartment level of mean pine (*Pinus* L), spruce (*Picea* A. Dietr.) and birch (*Betula* L.) stem volume were 29.3%, 43% and 65%, respectively. The respective biases were -5.5%, 4.4% and 5.7%. The basal-area and mean stem volume were clearly underestimated in highly stocked stands. With respect to the relative standard errors, the variation between different assessor was 10.6% to 33.9%.

SWFI bias, i.e. systematic error, is related to relascope plot sampling. The assessor places the plots subjectively, ensuring that locations having either a more or less than average stock density is preferred. The greatest bias-causing reason is, however, the use of a too small relascope coefficient in large-dimensioned stocks (Saari & Kangas 2005), since some of the trees supposed to be included in the plot are not counted. This leads to an underestimation of the basal area and subsequently the stem volume. Saari & Kangas (2005) showed that the basal area in large-dimensioned stands is underestimated in relascope plot sampling by appr. 20%, leading to an under-estimation of 25% in stem volume.

Of the Finnish forest organizations the Forest Service and (most) forest companies have adopted continuous updating as a part of their forest-planning procedures. However, forest-planning in privately owned forests is still based on periodic planning inventories, usually carried out in 10-year cycles. In continuous updating, SWFI acts as input data. After the inventory, stand development and the effects of silvicultural treatments are simulated, using various models. In other words, the error sources related to continuous updating are the same as those present in forest-planning simulations.

In computational updating of SWFI, the quality of the input data describing the stand's present state has a decisive impact on the reliability of the output results (e.g. Ojansuu et al. 2002, Haara & Korhonen 2004b, Haara 2005). When decisions are made on the basis of updated forest resource data, it is important to be aware of the quality and reliability of the input data to be able to take into account possible risks.

3.1.5 Remote sensing

Remote sensing can be utilized for obtaining forest-related information at several levels. It can be carried out for purposes related to single trees, plots of varying size and shape, forest compartments or stands, forest properties or larger forested areas. Traditionally, it has been utilized in both SWFI and sampling-based plot inventories. The most recent technologies also enable measurements to be taken at the tree level. In addition to forest-planning and forest inventory, remote sensing can be utilized as the main or auxiliary source of information for the strategic and operational planning of wood procurement, timber logging and transportation, estate management, and planning and monitoring of silvicultural treatments.

The accuracy requirements of forest data vary, depending on their intended use. For example, when the logging possibilities and outturn structure of larger forested areas are analysed in long term strategic planning, it is important to have unbiased input data that also include information on smaller (more rare) forest strata. When operational activities (wood procurement or silvicultural treatments) are supervised, the requirement for unbiased input data may be somewhat relaxed. Wood procurement supervision requires information on the internal variation in compartments.

Medium-resolution satellite imagery in the optical wavelength region has long been applied in forest inventory (e.g. Kilkki & Päivinen 1987, Tokola 1988, Tomppo 1990a,b). Despite its great value in large-area inventories, it has been a disappointment in small-area mapping and operative forest-planning. The main reason is that after numerous efforts, the accuracy of estimates derived from medium-resolution satellite image interpretations has not been high enough at the stand or field plot levels - the mean volume RMSE has typically been between 55% and 60% at the stand level (e.g. Holopainen & Lukkarinen 1994, Hyyppä et al. 1999). At the plot level the RMSEs are even higher: 65-80% (e.g. Poso et al. 1999, Tuominen & Poso 2001). When the size of the target area increases, the RMSEs decrease relatively rapidly, being 10-20% (for mean volume) at the typical forest property level in Finland (over 25 ha; Tokola & Heikkinen 1995).

Methodologies for utilizing digital aerial photography have been intensely developed since the early 1990s. Initially, the focus was on feature-based estimations of forest characteristics at the plot or stand level (e.g. Holopainen & Lukkarinen 1994, Holopainen 1998, Holopainen & Wang 1998, Hyyppä et al. 2000, Tuominen & Poso 2001, Anttila 2002), later on tree-level two- and three-dimensional (2D and 3D) methodologies (e.g. Dralle & Rudemo 1996, Larsen & Rudemo 1998, Brandtberg & Walter 1999, Lehikoinen 1999, Pitkänen 2001, Korpela 2004, Korpela & Tokola 2006).

The radiometric differences within and between photographs, caused by the central projection and low imaging altitudes, significantly complicate the interpretation of aerial photography. The imaging geometry at the time of exposure and the vegetation structure will greatly affect the illumination and cause bidirectional reflectance effects (Kimes et al. 1980, Kimes 1984, Li & Strahler 1986, Kleman 1987, Leckie 1987, King 1991, Fournier et al. 1995), that can be observed in the form of variations in brightness, especially in airborne images, where objects in the direction of the incoming solar radiation expose their shady sides to the sensor and those in the opposite direction their illuminated sides. As a result, the same forest or vegetation type will have totally different reflectance values and textural features, depending on its position in the photograph. Empirical corrections for bidirectional reflectance have been applied successfully in aerial photographs (e.g. by Holopainen & Wang 1998, Tuominen & Pekkarinen 2004), video images (King 1991, Franklin et al. 1995, Pellikka 1998) and multispectral scanner data (Leckie 1987, Leckie et al. 1995).

Holopainen & Lukkarinen (1994) studied the use of digital colour-infrared aerial photography for estimation of compartment and plot characteristics, in which they attempted to rectify radiometric problems present in the imagery with empirical models. The relative standard errors for plot basal area, mean height and stem volume were at best 34%, 22% and 39% respectively.

During the late 1990s, aerial photography interpretation methods based on the mensuration of single trees were being developed along with the plot- and stand-level methods based on tone and textural features. Initially, single-tree mensuration was performed as a 2D interpretation (e.g. Dralle & Rudemo 1996, Brandberg & Walter 1999, Larsen & Rudemo 1998, Lehikoinen 1999, Pitkänen 2001). The principle was to first locate single-tree crown tops in the image, using local tone maxima, after which the entire crown was delineated, using automatic segmentation. Then tree species was determined, using various image features. Next, tree diameter was estimated, using interpreted crown size and tree species as independent variables in allometric models, finally allowing the diameter/height distribution of the plot or compartment in question to be determined. However, without tree height information the model errors in the allometric models were so high that the final accuracy of 2D interpretation was insufficient for operational forest-planning purposes. For example, Lehikoinen (1999) arrived at a relative plot-level mean stem volume standard error of appr. 44%. Automatic segmentation, a phase of 2D interpretation, can also be utilized for semi-automatic delineation of stands, determining sampling units in feature-based methods and rectifying radiometric distortions (Pekkarinen & Tuominen 2003, Pekkarinen 2004, Tuominen & Pekkarinen 2004).

In summation, it can be stated that the resulting accuracy of both feature-based and 2D aerial photography methodologies is better than that of mid-resolution satellite imagery but is clearly poorer than that of traditional SWFI. The same accuracy level found in feature-based interpretation of numerical aerial photography can currently also be achieved, using very high resolution radar satellite imagery (Tokola et al. 2007, Holopainen et al. 2010b) the additional advantage of which is its high temporal resolution, i.e. the imagery can be obtained under all kinds of imaging conditions.

During the past 10 years, 3D methodologies based on digital photogrammetry and small footprint airborne laser scanning have experienced a major technological leap in forest inventory. With respect to the estimation of both stand mean stem volume e.g. Næsset 1997a, 1997b, 2002, 2004, Holmgren 2003) and single-tree characteristics (e.g. Hyyppä & Hyyppä 1999, Hyyppä & Inkinen 1999, Korpela 2004, Maltamo et al. 2004, Korpela et al. 2010), it has become possible to achieve at least the same level of accuracy as that found in traditional SFWI.

The concept of producing forest stand profiles, using laser profilers was demonstrated as early as around 1980 (e.g. Solodukhin et al. 1977, Nelson et al., 1984, Schreier et al., 1985). Nelson et al. (1988) demonstrated that the tree height, stem volume and biomass can be predicted with reasonable accuracy using reference plots and averaging of laser profiles.

Small-footprint ALS is a method based on laser (lidar) range measurements from an aircraft and the precise orientation of these measurements between a sensor, the position of which is known by using a differential Global Positioning System-(GPS) technique, and a reflecting object, the position of which (x, y, z) is to be defined (Hyyppä et al. 2009). The ALS gives the georeferenced point cloud, from which it is possible to calculate digital terrain models (DTMs), digital surface models (DSMs) and 3D models of the object (e.g. canopy height model CHM or normalized surface model nDSM). In addition to the point-cloud data, the intensity and sometimes the full waveform of the target can be recorded. Overview of laser-scanning technology can be found e.g. in Baltsavias (1999), and of using ALS in forest inventory in Næsset et al. (2004), Holopainen & Kalliovirta (2006), Hyyppä et al. (2008, 2009) and Koch et al. (2009).

The two main approaches in deriving forest information from small-footprint ALS data have been those based on laser canopy height distribution (Næsset 1997a,b, here an A_ALS method) and individual tree detection (ITD, Hyyppä & Inkinen, 1999). In the A_ALS method, percentiles of the distribution of laser canopy heights are used as predictors to estimate forest characteristics in some sampling area. For example, Næsset (1997b, 2002, 2004), Lefsky (1999), Magnussen et al. (1999), Means et al. (1999), Lim et al. (2003), Holmgren (2003) and Magnusson et al. (2007) showed that this approach produces highly reliable estimates of stand-level mean forest variables (e.g. mean volume). The current data acquisition cost is comparable to that of SWFI, since low pulse density ALS data can be utilized.

By increasing the number of laser pulses per m^2, individual trees can be recognized (Hyyppä & Inkinen 1999, Persson et al. 2002, Popescu et al. 2003, Leckie et al. 2003, Koch et al. 2006). In the ITD method, tree height and crown width are measured and tree species determined, using high-density laser-scanning imagery (more than 2-5 pulses/m^2). Based on this information, e.g. allometric models may then be derived (Kalliovirta & Tokola 2005) by which tree diameter and stem distribution at the plot or stand level may be finally estimated. The incorporation of tree height in the (allometric) models reduces model errors significantly compared with 2D methodologies. Hyyppä & Inkinen (1999) were the first to demonstrate an ALS- based ITD method in which maxima in the CHM were used for finding trees and segmentation for edge detection. In this way 40-50% of the trees in coniferous forests could be correctly segmented. Persson et al. (2002) improved the crown delineation and were able to link 71% of the tree heights with reference trees. Other attempts to use a tree-based approach have been reported, e.g. by Brandtberg et al. (2003), Vauhkonen (2010), Vauhkonen et al. (2010) and Korpela et al. (2010).

Due to its lower pulse density, the A_ALS method is the more cost-efficient approach. However, the ITD approach provides means for assessing the stand diameter or height distribution which is, in turn, invaluable in forest-planning-related simulation and optimization, logging operation planning and wood supply logistics.

Laser data provide accurate tree height information, which is missing from single aerial photographs, whereas digital aerial photos provide more details of the spatial geometry and more colour information that can be used for classifying tree species and health. Both provide information on crown shape and size. There have been many attempts at integrating laser scanner data with aerial imagery (e.g. Leckie et al. 2003, Persson et al. 2004, Packalen & Maltamo 2006, 2007).

The 3D ALS measurements are best at deriving elevation models (e.g. Kraus and Pfeifer 1998, Vosselman 2000), hence the NLS of Finland has initiated a pilot project for acquiring laser-scanning coverage for all of the country. In addition, all major Finnish forest organizations are currently constructing new operational systems for utilizing the new 3D methodologies.

ALS-based methodologies are also interesting from the standpoint of monitoring change, because they can be used even for measuring single-tree growth (Yu 2007). Tree growth can be determined in various ways using tree heights measured at different points in time (Yu et al. 2004), differences in DSMs, tree height histograms derived at different points in time (Næsset & Gobakken 2005) or differences in single-tree volume estimates estimated at different points in time.

Yu et al. (2006) showed that single-tree height growth can, at best, be measured with a standard error of 0.14 m, using multitemporal ALS imagery (10 pulses per m^2). The duration of the time interval between ALS imaging runs is critical, since under conditions of slow growth the average height increment is so modest that it cannot be reliably measured, using either ALS-based or traditional field inventory methods. Yu (2007) therefore concluded that the reliability of ALS-based growth measurements is better at longer imaging intervals.

ALS-based measuring of stock growth is also interesting from the standpoint of forest property valuation. A stand’s value is closely related to the site’s wood production capability, which could be determined using either increment measurements taken in the field or more simply dominant height estimated with ALS and stand age according to existing forest inventory data (Holopainen et al. 2009, 2010a).

ALS inventory has also been utilized in several ecological applications, for example in assessing biodiversity indicators such as coarse woody debris (Pesonen et al. 2010), identification of stands with high herbaceous plant diversity (Vehmas et al. 2009) and mapping defoliation (Solberg et al. 2006, Solberg 2008). Forests are one of the major carbon sinks in the global ecosystem. Because the canopy height, biomass, and carbon pools are functionally related, canopy height, which can be measured accurately by means of ALS, is a critical parameter in terrestrial carbon cycle (Kellndorfer et al. 2010). The leaf area index (LAI) has also been used as a measure of biomass (Koch 2010), and it has been successfully mapped with ALS, using ground calibration (Solberg 2008, Solberg et al.2006, 2009).

3.2 Uncertainty in growth models

The growth of trees and stocks is a highly significant characteristic that is often used in forest-planning and the computation of forestry yield value. From the standpoint of forest property valuation the rate of growth is a decisive factor with respect to rotation length and therefore influences forestry yield value computations to a great extent. In addition, a site's wood production capability is taken into account in determining the bare land value in the summation approach. Since tree growth cannot be directly measured, it must be estimated by models based on other measurable tree characteristics. Growth models can be divided into tree- and stand-level models (e.g. Mäkinen et al. 2010).

Forest growth simulators are applied for updating measured forest resource data and for predicting future growth to assess silvicultural measures and time of loggings (Burkhart 2003). Growth simulators incorporate numerous models for predicting various forest characteristics and their development. These models can never completely portray the underlying phenomena and their output estimates therefore include a degree of uncertainty. The degree of uncertainty is dependent on the functioning of individual models and the interaction between them. Models applied for simulating forest growth form a complex entity that often complicates the analysis of individual model uncertainty (Kangas 1999, Mäkinen et al. 2010). The uncertainty present in the simulation input data also influences the degree of uncertainty found in the output results (Mäkinen et al. 2010).

It is difficult to obtain reliability statistics on simulated stock characteristics, because the complex computing system embodies several sources of error. The most obvious source of error is uncertainty related to the prediction models, which can be classified into the following four main sources (Kangas & Kangas 1997): 1) the model's residual error, 2) uncertainty in model coefficients, 3) errors in dependent model values and 4) errors related to the specification of the model. In addition, spatial and temporal correlations present in different prediction errors cause problems in assessing degrees of reliability. Furthermore, differences in model and application populations may lead to biased output results.

Forest planning-related simulation computations are carried out either with stand- or tree-level simulators and models. The input data of computation systems based on tree-level models (used solely in Finland) include inventory errors and conversion errors that are generated when stand-level inventory data are transformed to tree-level data required by the system. Inventory error consists of sampling error, measurement error and computational error (Ojansuu et al. 2002).

One way to classify growth models is to partition them into empirical statistical models and process-based models. In the empirical model approach, the relationships between measurable tree characteristics, such as DBH, and growth, are modeled on the basis of material usually measured in the field. It is fairly risky to apply empirical models in cases that notably differ from the models' compilation material. In the process-based approach, dynamic ecological and physical processes are analysed, instead of working with empirical observations measured in the field. These processes deal with tree and stand photosynthesis, carbon and water balances and the absorbing of nutrients (Hari 1999, Mäkelä et al. 2000).

However, the classification of growth models into empirical and process-based models is not always clear, since in the process-based approach submodels are often derived using empirical measurement and modelling (Mäkelä 2007). Indeed, future, studies of growth will probably make use of prediction by hybrid models incorporating features from both above-mentioned modelling approaches.

3.3 Timber price development

The development of timber assortment prices is one of the most significant factors in forest property valuation computations. A major part of a stand's yield value is generated at the final logging, in which case the timing of the final logging and the prices of the most valuable timber assortments (saw-wood and intermediate logs) at that time are especially important. Saw-wood log outturn is, in turn, influenced by the (company-specific) bucking rules and quality criteria in effect at that time. Timber prices at the stand level are further influenced by logging conditions, size of the logging site and near-hauling distance. A majority of the forestry products manufactured in Finland are exported; therefore, raw timber prices are ultimately dependent on the demand for the end products in the world market. In addition to the price development of saw-wood and pulpwood, new timber assortment energy wood must be taken into account in future forest valuation.

Usually, an average price calculated on the basis of real stump prices over a certain, e.g. 10-year period of time is used in forest valuation computations. However, Airaksinen (2008) did not warrant time periods this long, because changes in stump prices are reflected in forest market prices with a delay of 1-3 years. This does not favour the use of long-term price trends in drawing up expected stump price and revenue forecasts. Airaksinen (2008) showed that prevailing stump prices should be used, especially when the forest property to be valuated possesses large quantities of stock ready to be sold.

Future stump prices can be predicted, using realized time series by which long-term trends can also be depicted and factors causing price peaks identified. The basic assumption then is that future price development is in accordance with past development. However, the reliability of future stump price predictions is generally rather poor (Viitala 2002). The greatest difficulty is related to the anticipating of future changes in society and various markets.

In Finland raw timber price time series are compiled by the Forest Research Institute (Metla). Time-series based empirical analyses of the development of raw timber prices were carried out at the Pellervo Economic Research Institute (PTT), Finland. Interest was focused on the return of forest capital (Tilli 1998a), regional variations in timber prices (Tilli 1998b) and the influence of imported wood on raw timber prices (Toivonen et al. 2000). Analysis of empirical time series has, however, often yielded contradictory results depending on the time series analysed (Viitala 2002).

3.4 Variations in the rate of interest

If a forest is considered as an investment there are several additional special features to be taken into account, compared with most alternative investment targets (Viitala 2002). The most important specialities are the long time span associated with wood production and the vast amounts of capital bound in the production. A third important feature is that most of the yields are generated at the end of the rotation period as a result of regeneration loggings, whereas most of the costs at the beginning of the rotation period are the result of forest regeneration activities. The study period is therefore of decisive importance when forestry yield and the rate of interest are considered.

From the investor’s point of view, the expected yield, associated risks and liquidity of the forest and alternative investment targets are crucial. The demand for raw wood has been stable for a great number of years, which decreases the risks associated with forest investment.

The interest rate used in forestry yield value computations has usually been in the range of 2-5%, which corresponds to real yields achieved in the long term (Viitala 2008). In the computation of tabulated soil and expectance values obtained by the summation approach, interest rates of 3.5% and 2.5% have been used in southern Finland and northern Finland, respectively (Paananen 2008).

The forest investment-related real yield varies somewhat, depending on the study period. During the years 1972-2005, the nominal forest yield has been almost 8% in Finland, but when inflation is taken into account it has remained at appr. 2% (Uotila & Lausti 2007). Uotila (2005) showed that during the years 1983-2003 the real yield associated with forest ownership was only 1.6%, due to the depression during the early 1990s and the deflation of real stump prices. During the years 1983-2005 an average real yield of appr. 3% was achieved (Viitala 2008). With respect to the expected yield and risk level, forest investment can thus be considered as a medium much like other investment in real estate (Airaksinen 2008).

3.5 Optimal rotation length

Solving of the optimal rotation length has been one of forest economics' major interests since the 18th century. In Finland, the subject has been studied by many, including Blomqvist (1893), Ericsson (1903), Nyyssönen (1958), Ilvessalo (1965), Ollikainen (1984), Kuuluvainen (1989), Valsta (1993), Tahvonen et al. (2001), Hyytiäinen & Tahvonen (2001, 2002, 2003), Viitala (2002) and Hyytiäinen (2003).

Forest rotation can be determined by 1) the trees' maximum biological age, 2) the maximum wood production, 3) a technical measure such as a minimum DBH, 4) the single rotation model, 5) the maximum forest interest, 6) the maximum land interest, 7) the maximum internal interest or 8) marginal profitability (Viitala 2002). In practice, the most important methodologies for determining the optimal rotation length and therefore also the most interesting alternatives from the standpoint of forest real estate valuation are the maximum forest and maximum land interest approaches.

In practical forestry, rotation length is determined by tree- or stand-level simulation and forest property-level optimization computations incorporating current forest legislation and recommendations (e.g. Forestry development Centre Tapio 2001, 2006). These are, in turn, based on objectives derived from the normal forest concept, such as sustainable and even logging outturns and evenness of the age class distribution (e.g. Ericsson 1903, Lönnroth 1930).

Conflict between the normal forest ideals and the optimal rotation length of a stand has been pointed out in numerous studies (e.g. Valsta 1993, Salminen 1993, Miina 1996, Vettenranta & Miina 1999, Hyytiäinen & Tahvonen 2001, 2002, 2003). However, several forest economists have also concluded that observing normal forest objectives will, in fact, improve the solution to the optimal rotation length problem, especially under circumstances of uncertainty (e.g. Heaps 1984, Tahvonen 1998). Optimal rotation length and how close to the normal forest structure it is worthwhile to strive are dependent on the loan limitations of the decision-maker, form of the utility function and the subjective required rate of return, market rate of interest, increment functions of various forest age classes and the current age class distribution.

3.6 Methods for accounting uncertainty in stock and yield computations

A simple and effective way to assess the uncertainty in growth and yield models is to model observed (past) errors in the characteristics of interest (Kangas 1999). The errors observed are defined as the difference between the predicted model and empirically measured growth. When growth and yield model uncertainty is empirically assessed it should be noted that the results are always material-dependent and concern past growth only. It is therefore risky to extrapolate these results to other regions and to future situations. Measurement errors in empirical data should also be taken into account (Kangas & Kangas 1997, Ojansuu et al. 2002).

The reliability of the output results by simulation models can be determined, using Monte Carlo (MC) methodology (e.g. Mäkelä 1988, Kangas 1997, 1999, Mäkinen et al. 2010, II, V, VI) or variance propagation methodology (e.g. Gertner 1987, Mowrer 1991, Kangas 1996). In both methodologies errors originating from different sources are combined into the total error. In the MC methodology confidence estimates are obtained by generating an error term from the model's error distribution for each output estimate. The model is run dozens or hundreds of times, the results of which are used to determine the final predicted value error statistics. A major advantage of the MC methodology is that by applying it input data or simulation errors can be analysed without a set of independent field data measured on two occasions.

Haara (2002) developed k-NN method for assessing the uncertainty of growth and yield predictions. The uncertainty of the predicted stand characteristics on the target stand was derived from the uncertainty assessments of growth predictions of the nearest neighbour stands. Haara (2002) concluded that quality of the *k*-NN method predictions depends on the availability of extensive reference data. Haara & Leskinen (2009) compared *k*-NN method (Haara 2002) and the models of observed errors for assessing the uncertainty of updated forest inventory data. They showed that the uncertainty assessments of updated stand-level inventory data using both methods found to be feasible.

Reliable inventory data are essential for forest planning. In assessing the state of a stand, the estimates may differ significantly from the real situation, due to the inventory method used. This aspect can be studied using cost-plus-loss analyses, in which the expected losses due to inoptimal decision making are added to the total forest inventory costs (Burkhart et al. 1978, Hamilton 1978). The cost-plus-loss approach was widely utilized in recent forest inventory- and planning-related research (e.g. Ståhl 1994a, 1994b, Eid 2000, Holmström et al. 2003, Eid et al. 2004, Duvemo & Lämås 2006, Barth & Ståhl 2007, Borders et al. 2008, Väisänen 2008, Duvemo 2009, I).

Forest inventory accuracy affects forest-planning simulation and optimization results. However, in the light of previous studies the effect is not unambiguous. Larsson (1994) showed that stock characteristic standard errors less than 10% do not yet lead to significant differences in regeneration (net) revenues given that inventory costs are also taken into account. Eid (2000) showed that errors in basal area and mean height did not significantly affect NPV, whereas errors in stand age and site quality had the greatest impact. These results probably indicate that the measurement accuracy of those characteristics used as input data is crucial to the development models of single trees or stands. Therefore, the significance of the accuracy of inventoried characteristics varies between different countries, depending on the simulation and optimization models used during the forest-planning computations (Väisänen 2008).

Väisänen (2008) compared the nonoptimal losses caused by errors found in visual estimation and area-based ALS carried out in 47 pine-dominant stands. Results of systematic plot inventory served as reference material. In contrast with previous studies (e.g. Eid et al. 2004, I), A_ALS inventory produced larger nonoptimal losses than SWFI. Väisänen (2008) deduced that this was due to that gravely underestimated stock age in the A_ALS inventory, leading to significant faults in the computed standwise treatment programmes. However, A_ALS turned out to be an extremely cost-efficient methodology.

If it is assumed that a certain event is solely dependent on its present value and not on its history, a method called the Brownian motion can be utilized. This method has been used in modelling uncertainty in financial markets. In this method both history and market knowledge are reflected in the price of a given product. Furthermore the development of its expected value, variance and ever-increasing prediction of future variance can be predicted together with trends occurring over time. A special case of the Brownian motion, the geometric Brownian motion (GBM), which includes a trend, enables the prediction of uncertainty related to the return of invested capital. A problem related to the utilization of the GBM is that over time, linearly increasing prediction variance results in wide confidence ranges. In addition, it does not take into account the tendency of economic variables to assume a certain balance or average value over a long period of time. (Viitala 2002)

Timber prices fluctuate heavily in the short run. However, Dixit & Pindyck (1994) suggested that if data were available for only 30-40 years, it would be difficult to distinguish statistically between random walk (GBM) and mean-reverting (geometric mean-reverting, GMR) processes. As a result, the decision on price model should be based more on common understanding of the nature of the price process rather than outcomes of the statistical tests. In the short run, the prices of raw commodities tend to fluctuate, but in the longer run they will draw back towards long-run marginal cost of their production. In the forest economics literature, GBM has been widely applied due to its tractability. Clarke & Reed (1989), Thomson (1992) and Yoshimoto & Shoji (1998) supported the use of GBM. On the other hand, Insley (2002), Insley & Rollins (2005) and Yoshimoto (2009) chose the GMR process. Although there is no analytical solution for the GMR process, they chose it based on economic reasoning.

Stock growth uncertainty has been modeled also using GBM, GMR and stochastic simulations (Viitala 2002). Valsta (1992) showed that stock increment uncertainty and the possibility of natural damage lengthen the optimal rotation period and lead to more intensive thinnings. Valsta (1992) also concluded that the functionality of mortality models is in fact more decisive than the functionality of growth models. Clarke & Reed (1989) and Reed & Clarke (1990) investigated the effect of value growth-related uncertainty on the optimal rotation period length. Trends in timber prices were assumed to comply with GBMs. Stock increment was dependent on stock age or stock stem volume and density. The results suggest that optimal rotation period length is highly dependent on the forest owner's attitude to risk and his/her expectations as related to stump prices and stock growth.

Leskinen & Kangas (2001) used expert opinions for estimating the development of timber prices over the next 20 years. The experts were divided into three groups according to their background: research, industry and forest owner. Clear differences in expected prices were found between the groups: all groups assumed that raw timber prices would slightly increase but the forest owner group's expectations were higher than the other groups regarding all timber assortments. Leskinen & Kangas, J. (2001) and Kangas, J. et al. (2000) showed that this methodology was feasible for determining tactical forest-planning logging revenues and their corresponding uncertainty.

Attfield et al. (1991) showed that as a part of adaptable decision-making forest owners' set themselves a minimum price by which they were prepared to conduct timber trading. This minimum price is dependent on the value increment and amount of wood and may therefore vary among stands. Several studies (e.g. Haight & Holmes 1991, Thomson 1992, Plantiga 1998, Brazee & Bulte 2000) have shown that following the use of minimum prices, forestry net yields have increased markedly. However, minimum price profitability is dependent on the nature of timber price development. If timber price development accords with the GBM, i.e. if periodic timber prices are not dependent on each other and can be extracted from some probability distribution, there are no grounds for using minimum prices (Clarke & Reed 1989, Thomson 1992, Yin & Newman 1995).

Pukkala (1997) showed that computations including risk analysis should be adopted as an alternative in deterministic forest-planning. The methodology in question is stochastic optimization, using scenarios. Optimization can be based either on mathematical programming (e.g. linear programming) or iterative methodologies. In the utility theoretical approach, the decision maker's preferences are estimated, using an explicit utility function. In the optimization phase, the forest treatment programme maximizing the utility function, i.e. providing the maximum benefit, is sought.

In the scenario technique several development alternatives are generated for factors causing risk and uncertainty (Pukkala 1997). Scenarios may be produced e.g. for wood prices, growth levels, successful artificial and natural regeneration and rate of tree mortality, but also for preferences and input data (accuracy). Preference scenarios imply variation in utility function coefficients. Input data (accuracy) scenarios imply, in turn, the addition of systematic and random errors according to those generally found in computation input data obtained by various inventory methodologies (Pukkala 1997). Scenarios may be produced as realizations of (random) stochastic models. Eriksson (2006) utilized stochastic process and a collection of scenarios to account uncertainty in large-scale long-range forest management problems. His approach took account that the decision maker is able to observe the state of the system over time and subsequently make adaptions.

Pukkala (2006) studied the effect of assortment prices and interest rate on the economically optimal timing of loggings. The models in Hynynen et al (2002) were used for simulating stand development. Optimization was carried out, using a stand-level methodology developed by Pukkala (2005), which maximized the stand's yield value (see also Hyytiäinen 2003). Pukkala (2006) showed that when a stand's yield value is minimized, the interrelationship between saw-wood and pulpwood prices and the interest rate used determine the stand's optimal rotation length or time of the final felling. The assortment price relationships did not, however, have as great an impact on the timing of thinnings. The increase in saw-wood relative price lengthens the optimal rotation period and the increase of pulpwood relative price in turn shortens it. Increase in the interest rate shortens the rotation period, decreases the optimal stock density and alters thinning, such that it is worthwhile to remove larger trees. Similar results were found, e.g. by Hyytiäinen (2003).

Traditionally studies of growth and yield uncertainty (e.g. Gertner & Dzialowy 1984, Mowrer 1991, Kangas 1997, 1999) have mainly focused on the influence of various uncertainty components in growth model functioning. However, Mäkinen (2010) and Mäkinen et al. (2010) showed that instead of analysing individual models, the model chains implemented by the simulators should be scrutinized as a whole.

A common way to portray uncertainty is to estimate distribution statistics along with the single figure or so-called point estimates (Mäkinen 2010). For example, various forest characteristics measured in the field can be described using both mean and standard deviation statistics. This procedure naturally requires information on the magnitude and distribution of various measurement errors related to the measuring methods applied (Mäkinen & Holopainen 2009, Mäkinen 2010). Uncertainty related to forest growth predictions can also be depicted using distributions. This, however, requires information on the error distributions of the applied growth models. Future timber price prediction has been modeled using a variety of approaches. The resulting price models are most commonly random models where the degree of price fluctuation is determined on the basis of historical price series. Modelling of uncertainty related to the estimation of forestry yield requires information on the error distributions related to the basic forest inventory data and related growth predictions as well as on the random behavior of the timber price model applied. MC simulation can be used in this procedure (II, V and VI). Below is a simplified description of the procedure used in V and VI (Mäkinen &

Holopainen 2009).

1. Random errors sampled from the error distributions related to inventory methodology applied in the studied case were added to the input data used in the simulation process.
2. Forest development was simulated up to the next regeneration phase applying forest growth models the predictions of which were modified using random errors sampled from the respective error distributions.
3. Revenues and expenses related to various forest treatments especially various logging activities were predicted using various random price and cost models.

Phases 1-3 were repeated for a sufficient number of times for each studied stand.

These kinds of simulations result in large numbers of NPV predictions for each studied forest stand, namely the distribution of predicted NPV. The same analysis was carried out so that simultaneous uncertainty was caused by only one or some of the possible sources of uncertainty. This approach enables further analysis on the singular and combined effect of various sources of uncertainty on the distribution of predicted forest NPV.

3.7 Forest planning simulation and optimization systems in Finland

In Finland, the most commonly applied simulation and optimization software system is the MELA (MEtsäLAskelma, forest computation) system developed by the Finnish Forest Research Institute (Metla). MELA is a forest-planning tool consisting of a tree-level forest stand simulator and a linear optimization module (JLP, Lappi 1992). The simulator produces alternative stand-level treatment and development scenarios that are compared in the optimization sequence. During optimization, the maximum or minimum solution is derived for a linear objective function, given a set of linear restrictions (Lappi 1992, Siitonen et al. 1996). MELA's optimization task is open, meaning that it is totally up to the decision maker to define it, using MELA's more than 1000 decision variables or their linear combinations (Salminen 1999). Pekka Kilkki's dissertation "Income-orientated cutting budget" (Kilkki 1968) can be considered as the starting point of the MELA system.

A new more flexible forest-planning software system called SIMO (Simulation and Optimization, Tokola et al. 2006, Rasinmäki et al. 2009) has been developed at the Helsinki University Department of Forest Resources since 2004. The objective of the SIMO project has been to develop a simulation and optimization software system having the ability to use as input data any level or scale (tree, plot, stand level) of forest inventory data having any level of accuracy. In other words, with the SIMO system it is possible to flexibly modify the data content and set of models upon which the simulation of forest development is based. It is also possible to take the requirements presented by multiobjective forest-planning better into account than in the MELA system. The system's model library includes more than 400 tree or stock size, growth, development, mortality, treatment and wood production models, based on the most recent research results. In the next version of the system it will also be possible to utilize spatial models related to the spatial order of trees and stands. A central objective of the system is to produce confidence level information related to the output results, which forest-planning computations have so far lacked.

The MONSU software system (e.g. Pukkala 2005), developed at the University of Joensuu, is also able to take into account other than wood production-related objectives. Spatial optimization is also supported. The Tapio tables (Paananen 2008) utilized in the summation approach are, in turn, currently derived with the MOTTI forest stand simulator (Hynynen et al. 2002), the tree- and stand- level models of which are similar to those found in the MELA, SIMO and MONSU software systems.

4 Results of the separate studies

4.1 Structure of the study

Studies I, II and III focused on analysing the effects of inventory data uncertainty on forestry yield value (NPV) simulation computations. Studies I and II were more theoretical in nature and focused on achievable results, given that measurement and estimation accuracies reported in previous studies remain the same level or similar. With respect to remote-sensing interpretation, Studies I and II focused on single-tree-level aerial photography and ALS applications. In study III we investigated the theoretical benefit of using tree species-specific inventory data instead of stand-level mean data in forest-planning simulations. In study IV we focused on determining the accuracy of timber assortment-level data produced by practical SWFI and ALS inventory methodologies. In addition to inventory data uncertainty, we investigated and incorporated two other central sources of uncertainty, namely growth model errors and fluctuation of raw timber prices in stand-level (V) and in forest property level (VI) yield estimations.

4.2 I

The objective was to clarify the value of forest inventory data in forest-planning simulation computations. We applied the cost-plus-loss approach, according to which costs resulted from inoptimal decision-making as a consequence of inaccurate inventory data were added to the actual inventory costs. We focused on determining the effects of uncertainty in the forest inventory data used as input data to the simulation computations on the NPV of logging incomes and the magnitude of subsequent logging income losses.

The study material concerned a Helsinki City forested area (700 ha) for which a nature management standwise database was made available. In addition to the accuracy of the SWFI data, the accuracy of data derived by 2D interpretation of digital aerial photography and 3D interpretation of aerial photography and laser-scanning data were scrutinized. The 2D interpretation signifies a method in which single tree crown diameters are first measured from automatically segmented digital aerial photographs. The diameters measured were then used as an independent variable in models estimating single-tree DBH. In the 3D method, single-tree height measured either from aerial photographs or laser-scanning data photogrammetrically was also produced. The accuracy statistics concerning the various inventory methods were adopted from available data. The cost-plus-loss analyses were carried out with the MOTTI simulator.

The SWFI cost prevailing at the time of the study (17 €/ha) was used as the forest inventory data production cost for this inventory methodology. We also determined that the production of forest inventory data using the 2D or 3D interpretation of large-scale (scale 1:16000 or better) aerial photography or high-density (pulse density > 5 pulses per m^2) laser-scanning data in forested areas larger than 10000 ha would cost approximately the same as traditional SWFI. In addition to acquisition costs, preprocessing and mensuration costs were also taken into account when the total costs of the interpretation of aerial photography and laser-scanning data were estimated.

A salient result of the study was that the inaccuracy of forest inventory data led to significant optimality losses, due to the mistiming of loggings. The inventory data derived by the 3D interpretation of either aerial photography or laser-scanning data were able to compete with traditional SWFI data. The data derived by 2D interpretation were, however, too inaccurate, leading to clearly greater optimality losses than data derived by SWFI or 3D interpretation.

Estimation of inventory costs proved to be the study's black spot, since per-hectare costs are highly dependent on inventory area size: the larger the inventory area the lower the per-hectare costs. The rapid development of remote-sensing techniques also resulted in further challenges to inventory cost estimation. Laser scanning instruments have evolved especially quickly. For example, flight altitudes can also be increased as a consequence of increasing scanning density, leading to lower per-hectare costs. It is therefore probable that future high-density laser-scanning data will be made available at the current price of low-density data. On the other hand, one should bear in mind that in interpretation of remote-sensing data, most costs stem from data processing and acquisition of field reference data.

However, we clearly highlighted the importance of input data accuracy with respect to the derivation of optimal forest-logging programs. Our results also justify the undertaking of economic investments to improve inventory data accuracy and to use the best possible remote-sensing, e.g. laser-scanning, data.

4.3 II

In I we dealt with city forests, although inventory data uncertainty and cost figures were adopted from previous results in commercial forests. In II these analyses were continued with commercial forest material. The objective here was, as in I, to investigate the effects of input data uncertainty on the simulation results of logging timing and NPV. The analyses were restricted to ITD ALS inventory methodology, which was compared with traditional SWFI methodology. In addition, the functionality of stand-level and single-tree-level simulators, using various input data, was investigated. Due to uncertainties related to actual inventory costs, the cost-plus-loss approach was not adopted and the analyses were focused on the effect of inventory data accuracy on the timing of loggings and the NPV of thinning and clear-cutting revenues. Forest-planning computations were carried out with the SIMO simulator, using MC simulation.

The input data for the SIMO simulations consisted of forest-planning SWFI data and data measured for 270 fixed-radius circular plots in an appr. 2 000 ha large research forested area located in the vicinity of Evo (southern Finland). The uncertainty statistics concerning input data accuracy were adopted from previous research results. Figures concerning the ITD ALS methodology were adopted from a recently completed investigation (the EUROSDR report, Kaartinen & Hyyppä 2008, Kaartinen et al. 2008) (European Spatial Data Research Network, Dublin, Ireland), in which results of 11 different ITD algorithms developed by an international research group were compared in the context of a single research area located in Espoonlahti (southern coast of Finland). The best of the 11 algorithms investigated was chosen as the algorithm to be applied in this study.

The results suggest that input data accuracy significantly affects both logging timing and logging revenue NPV. With respect to logging timing, inaccurate inventory data caused an error in thinning or clear-cutting timing, ranging from 6.5 to 10.3 years, depending on input data source and simulation methodology. In considering that the average interval between loggings in Finland is appr. 20 years, we suggest that inaccurate inventory data cause a significant error in the simulated timing of loggings. With respect to simulated logging revenue NPV, inaccurate inventory data caused a relative error ranging from 28.2% to 57%.

The results showed that ITD leads to a more accurate simulated timing of loggings than the traditional SWFI, given that ITD ALS inventory accuracy corresponds to that of the most accurate algorithm presented in the EUROSDR report. It must be noted that the range of ALS accuracy figures presented in the EUROSDR report was quite considerable. In addition, tree species recognition was assumed to be faultless which, at least currently, is quite unrealistic. Tree-level simulation produced slightly more accurate results than stand-level simulation. However, it was concluded that current simulation models are not able to fully utilize the accurate tree height information produced by the ITD ALS inventory methodology.

4.4 III

In III we investigated the theoretical benefit of using tree species-specific inventory data instead of stand-level mean data in forest-planning simulations. This comparison was based on timing differences in thinning and clear-cuttings during a 20-year simulation period. The development of stand characteristics (age, basal area, volume, dominant height, mean height, mean diameter) in those stands not harvested during the simulation period was also scrutinized. The calculations were performed with SIMO simulation and optimization software.

The results showed that the use of tree species stratum data in forest-planning simulations is highly relevant from the standpoint of both the development of stand characteristics and the timing of logging operations. The relative standard errors stemming from the level of input data varied from 2.1% to 20.6% and from 58% to 84% in stand characteristics and timing of logging operations, respectively. The significance of the stratumwise input data culminated in the functioning of the specieswise growth models at different stages of stand development. Study III highlighted the importance of tree species stratum data in forest-planning simulations and yield value estimations.

4.5 IV

Our results (II) shed light on the degree of accuracy that the ALS single-tree methodologies (individual tree detection, ITD), currently still in the research stage, will probably achieve in future operative forest planning. The figures describing simulation input data accuracy were adopted from existing studies (I, II). In IV a practical test was carried out with forest inventory methods either currently in use or for near-future applications. The objective of the study was to compare SWFI with A_ALS and aerial photography inventory with respect to assessing timber assortment-level forest data. We focused on the estimation of timber assortment quantities, economic values and related sources of uncertainty. In addition to inventory errors associated with the generation of stem distributions, estimation of single-tree stem form and simulation of bucking during the forest-planning simulation computations were scrutinized.

Timber assortment outturn data gathered by logging machine were applied as the study's ground truth data. These data were acquired from 31 logging sites (5950 trees) logged in the Evo area during winter 2008. The data consisted of timber assortment volumes measured by the logging machine. For clear-cutting sites (12), accurate timber assortment outturn volumes were known for each stand. With respect to thinning sites (19) determination of stand-level figures was based on the measurement of 90 circular plots that were measured before and after the logging operation. Uncertainty caused by the investigated sources of error was analysed, using simulation computations performed by the SIMO system. A_ALS feature selection was based on the genetic algorithm method presented by Holopainen et al. (2008) and estimation of forest characteristics on the nonparametric *k*-NN method.

The results showed that the most significant source of error in the prediction of clear-cutting assortment outturns was inventory error. The bias and root-mean-squared error (RMSE) of inventory errors varied between -11.4 and 21.6 m^3/ha and 6.8 and 40.5 m^3/ha, respectively, depending on the assortment and inventory methodology. The effect of forest inventory errors on the value of logging outturn in clear-cuttings was 29.1% (SWFI) and 24.7% (ALS). The respective RMSE values related to thinnings were 41.1% and 42%.

The errors related to stem distribution generation, stem form prediction and bucking simulation were significant but considerably lower in magnitude than the inventory error (see Table 1). Timber assortment-level errors were greater than those related to mean characteristics (e.g. mean stem volume) estimation. This is a consequence of errors stemming from stem distribution generation and stem form prediction, bucking simulation and also uncertainty in tree species recognition.

Effects of A_ALS inventory error, SWFI error, stem distribution generation error, stem form prediction and bucking simulation error and their combined effects to the predicted stock value (bias% and rmse%) are summarized in Table 1.

Table 1. Effects ($bias\%^{NPV}$ and $rmse\%^{NPV}$) of different error sources on predicted stock value (€/m^3) at stand level. Field reference measured by logging machine: 5400 trees within 12 clear-cutting stands. A_ALS = area-based ALS inventory, SWFI = standwise field inventory. The active error source is marked with X.

ERROR SOURCES				Predicted stock value	
A_ALS Inventory error	SWFI inventory error	Stem distribution generation	stem form prediction & bucking simulation	$bias\%^{NPV}$	$rmse\%^{NPV}$
X				0.6	24.7
	X			-0.1	29.1
		X		-1.2	2.6
	X	X	X	2.5	33.4
X		X	X	4.2	23.8

4.6 V

In I-IV we focused on one source of uncertainty related to forest property valuation only, namely inventory data inaccuracy (including inaccuracy in stem distribution generation, stem form prediction and bucking simulation). In V the analyses were broadened to also take into account two other central sources of uncertainty present in current forestry yield value computations. Our objective was to compare uncertainty related to inventory data, growth models and fluctuation in raw timber prices in forestry yield values (NPV) computed throughout the rotation period. With respect to inventory data, uncertainty analyses were carried out for methodologies currently in operative use only, i.e. the SWFI and A_ALS inventory methodologies. The study was performed, using SIMO simulations and interest rates of 3%, 4% and 5%. The study material consisted of a simulated forest property of 40 stands having an even representation of various tree species and development classes. The uncertainty figures concerning inventory data accuracy were adopted from two southern Finland A_ALS pilot projects. The growth model uncertainty figures were derived, using the respective error models. Raw timber price fluctuation was predicted using a GMR price model and the realized price development of the period January 1986 and August 2008.

The results (Table 2) showed that the growth models used in forest-planning simulation computations were the greatest source of uncertainty with respect to NPVs computed throughout the rotation period. Uncertainty almost as great was caused by input data uncertainty, while the uncertainty caused by fluctuation of raw timber prices was considerably lower in magnitude. The interest rate used in the computations did not affect the relative importance of the various sources of uncertainty in any meaningful manner. Each single source of uncertainty caused an uncertainty in NPVs ranging from 8% to 33%. The joint effect was appr. 50% at most. Interestingly, the joint effects turned out to be significantly less than the sum of the respective sources of uncertainty.

Table 2. Averages of the relative biases ($bias\%^{NPV}$) and sds ($sd\%^{NPV}$) of the simulated NPV distributions with given source of uncertainty with 3% rate of interest. U_{PRICE} = The uncertainty caused by random variation in future timber assortment prices. U_{FIELD} = The uncertainty caused by SWFI errors. U_{ALS} = The uncertainty caused by A_ALS inventory errors. U_{GROWTH} = The uncertainty caused by random errors in growth projections. The active uncertainty sources in each combination are marked with X. (Table modified from V)

SOURCES OF UNCERTAINTY				Interest rate 3%	
U_{PRICE}	U_{FIELD}	U_{ALS}	U_{GROWTH}	$bias\%^{NPV}$	$sd\%^{NPV}$
X				-6.1	8.2
	X			-6.8	28.8
		X		1.7	26.5
			X	-9.5	33.2
X	X			-9.1	29
X		X		-1	27.4
X			X	-5.7	34.9
	X		X	-12.5	46.9
		X	X	-2.1	46.5
X	X		X	-9.2	47.4
X		X	X	0.1	46.5

The methodology developed during the study enables the computation of confidence levels for forestry yield value estimates. Furthermore, the importance of various sources of uncertainty is revealed and a concept of what to focus on to reduce uncertainty is provided.

4.7. VI

A property (or estate) is the unit in operational forest value estimations produced for the purposes of e.g. real estate business, land exchanges and land divisions. The effects of various sources of uncertainty on the value of forest property cannot be obtained simply by aggregating the uncertainties observed at stand level, because the deviations from average or true value estimates between various stands tend to partly cancel out each other (V). Thus, additional simulations were needed to obtain the overall level of uncertainty at the level and for typical size of forest properties (VI).

The objective of the VI was to analyse the effect of uncertainty factors related to forest inventory data, growth models and timber price fluctuation on the prediction of forest property-level NPV. The degree of uncertainty associated with inventory data was obtained from previous A_ALS inventory studies. The study was performed, applying the MC simulation, using stand-level growth and yield projection models and three alternative rates of interest (3%, 4% and 5%). Timber price fluctuation was portrayed with GMR price models. The analysis was conducted for four alternative forest properties having varying compartment structures: A) sapling stands, B) young thinning stands, C) a property having an even development class distribution and D) mature stands. Simulations resulted in predicted forestry yield value (predicted NPV) distributions at both stand and property levels. Results showed that A_ALS inventory errors were the most prominent source of uncertainty, leading to a 5.1-7.5% relative deviation of property-level NPV when an interest rate of 3% was applied. Interestingly, A_ALS inventory led to significant biases at the property level, ranging from 8.9% to 14.1% (3% rate of interest). A_ALS inventory-based bias was the most significant in mature stand properties. Errors related to the growth predictions led to a relative standard deviation in NPV, varying from 1.5% to 4.1%. Growth model-related uncertainty was most significant in sapling stand properties. Timber price fluctuation caused the relative standard deviations ranged from 3.4% to 6.4% (3% rate of interest). The combined relative variation caused by inventory errors, growth model errors and timber price fluctuation varied, depending on the property type and applied rates of interest from 6.4% to 12.6%.

Table 3. Comparison of results of stand-level (V) and property-level (VI) uncertainties (averages of the relative biases ($bias\%^{NPV}$) and standard deviations ($sd\%^{NPV}$). Property-level: a 25-ha forest property having an even development class distribution. Rate of interest 3%. U_{PRICE} = The uncertainty caused by random variation in future timber assortment prices. U_{ALS} = The uncertainty caused by A_ALS inventory errors. U_{GROWTH} = The uncertainty caused by random errors in growth projections. The active uncertainty source is marked with X.

SOURCES OF UNCERTAINTY			Stand-level (V)		Property-level (VI)	
U_{PRICE}	U_{ALS}	U_{GROWTH}	$bias\%^{NPV}$	$sd\%^{NPV}$	$bias\%^{NPV}$	$sd\%^{NPV}$
X			-6,1	8,2	-1,5	3,4
	X		1,7	26,5	12,2	5,1
		X	-9,5	33,2	1,4	1,7
X	X	X	0,1	46,5	13,2	6,5

Comparison of results of V and VI (Table 3) showed that the forest property level deals with a considerably lesser degree of NPV deviation than does stand level. Accuracy of the inventory method and growth models is strongly dependent on the size of inventory unit examined (tree, plot, stand, property) and its degree of internal variation (homogeneity), i.e. the larger and more homogeneous the inventory unit, the smaller the relative standard error achievable. The reduced variation in NPV due to price fluctuations, when shifting from stand level to property level, is a consequence of two factors. Firstly, the timing harvests and other silvicultural activities is different between stands in different development stages. Secondly, the timber species in various stands are different. Even though the prices of different timber assortments are strongly correlated, the relative differences in yearly increments of prices cancel out part of the uncertainty in property-level computations. In addition, the degree of uncertainty caused by timber price fluctuation was rather small, due probably to the form of the stochastic price model applied (GMR).

4.8 Main results

The main results were as follows:

1) Inventory errors led to significant mistiming of simulated loggings and subsequent prominent losses in simulated NPV(I, II, III).
2) It was shown (II) that tree diameter-based characteristics are the most important data in simulations. These characteristics, however, cannot be directly estimated by ALS. Accurately estimated tree / stand height improves simulation results indirectly through other characteristics. However, accurate height estimates cannot be fully utilized in current tree/stand models and simulators.
3) Tree species stratum data is important in forest-planning simulations and NPV estimations. The significance of the stratumwise input data in stand-level NPV estimations culminated in the functioning of the specieswise growth models at different stages of stand development (III), i.e. forest inventory methods should produce as accurate tree species stratum data as possible.
4) The most significant source of error in the prediction of timber assortment outturns was SWFI and A_ALS inventory error. The errors related to stem distribution generation, stem form prediction and bucking simulation were significant but considerably lower in magnitude than the inventory error (IV). Timber assortment-level errors were greater than those related to mean characteristics (e.g. mean stem volume) estimation.
5) Tree- and stand-level growth models applied in forest-planning simulation computations cause uncertainty in forest NPV computation results. It was shown that the growth models may cause errors in computed stand level NPV even greater than those caused by A_ALS / SWFI inventory error (V).
6) Fluctuation of raw timber prices causes uncertainty in forest NPV computation results. However, the effect of raw timber price fluctuation on computed NPV at stand-level turned out to be considerably less than that of A_ALS inventory error or growth model errors (V). In property level NPV deviation caused by timber price fluctuation was similar than NPV deviation caused by growth model errors.
7) It was demonstrated that in forest property level A_ALS inventory caused more uncertainty to the predicted NPV than growth model errors or uncertainty in timber price fluctuation. Forest property level deals with a considerably lesser degree of NPV deviation than does stand-level, however, A_ALS inventory error-related uncertainty caused significant bias in property-level NPV estimates.

8) The combined effect of A_ALS inventory error, growth model errors and raw timber price fluctuation is not equal to the error sum of these individual sources of error (V, VI).
9) The ALS ITD method led to a superior level of accuracy than traditional SWFI (II), but tree species recognition was then assumed to be faultless, which is not a realistic assumption. A_ALS interpretation led to accuracy levels similar or better to that of traditional SWFI (IV, V). It is, however, clear that the studied ALS inventory methodologies produce a different kind of uncertainty in forest-planning simulation computation results than the traditional SWFI methodology does. This uncertainty mainly deals with the generation of stem distributions.

5 Discussion

5.1 Effect of inventory methodology

5.1.1 Formation of stem distributions – starting point for forest-planning computations

Forest-planning simulation computations are based on measured or estimated stand-level stem diameter distributions. In traditional SWFI stem distributions are formed by models based on theoretical distributions, e.g. the probability functions of beta, Weibull, Johnson SB, percentile models and nonparametric models (Kilkki et al. 1989, Maltamo & Kangas 1998, Siipilehto 1999, Kangas & Maltamo 2000). Siipilehto (1999) showed that it is possible to improve the accuracy of predicted basal area-diameter distributions, using stem number observations in advanced stands. Malinen et al. (2001) developed application of the nonparametric most similar neighbor (MSN) method for wood procurement planning. They showed that the application was a flexible tool for predicting the characteristics of marked stands based on the stem data collected by a harvester. Prediction of stem form and simulation of bucking have been studied e.g. by Laasasenaho (1982), Lappi (1986), Uusitalo et al. (2004) and Koskela et al. (2006).

The input data for theoretical models are acquired by measuring stand basal area and tree data for a median tree having a diameter corresponding to the mean diameter of the stand on representatively placed relascope plots. The median trees are usually selected visually. This procedure can be considered as a major source of error in the SWFI. Median trees are also measured for height and the measurements are then used for deriving or calibrating tree height models. Tree height models are used to estimate heights for each diameter class in the stem distribution. Finally, diameter class and stand-level stem volumes are calculated.

The economic value of the stand or estate can be estimated, using forest management planning simulations. Forest planning is based on stand-level or tree-level models and simulators. When tree-level forest-planning simulators are used, stem distributions can be formed, based on mean stock characteristics, by determining and measuring the inventory unit (e.g. compartment) median trees and utilizing theoretical stem distributions, such as the Weibull distribution, in the modelling and derivation phases, or it can be derived by enumerating all trees present in the inventory unit, resulting in true stem distribution series.

A_ALS interpretation provides new opportunities but also challenges with respect to forest-planning computation procedures, e.g. it offers several alternatives for forming stem distributions. Forest organizations involved in the planning of privately owned forests in Finland are currently adopting a new inventory methodology in which A_ALS interpretation is implemented in a grid consisting of 16-m x 16-m cells. Forest characteristics are estimated for each cell, using the nonparametric k-NN or k-MSN algorithms. In this case stem distributions could be formed separately for each grid cell, which would enable better analysis of intra stand variation. However, stand-level mean values will be used for forming stem distributions at least for the time being, probably because of the heavy computations involved. Instead of using single grid cells as computation units, rudimentary compartments formed by automatic segmentation of grid cells could be used as well (Tuominen & Haapanen 2009).

A_ALS features can be utilized for the formation of stem distributions in several ways. One alternative is to first estimate the mean stand characteristics and then apply stem distribution models based on theoretical distributions (e.g. the Weibull distribution). Another alternative is to use ALS features to directly estimate stem distribution parameters in a manner proposed and studied by Gobacken & Næsset (2004), Maltamo et al. (2006) or by Breidenbach et al. (2008). Gobacken & Næsset (2004) and Maltamo et al. (2006) showed that size distributions of trees can be estimated, using locally modelled distribution functions in which ALS-based canopy height metrics are used as predictors. It is also possible to utilize stem distribution series measured for field plots as reference in k-NN or k-MSN method (Packalén & Maltamo 2008, Packalén 2009).

The greatest advantage of single-tree ALS interpretation over A_ALS interpretation is that at least a major part of the stem distribution can be derived directly from the interpretation results. Smaller-sized trees often go unnoticed, but they can be taken into account using theoretical stem distributions (e.g. Maltamo et al. 2004).

It should be pointed out that here (IV) we focused on uncertainty of current forest management-planning simulation methods in Finland, i.e. despite promising results of other opportunities to utilize area-level ALS inventory data (Gobakken & Næsset 2004, Maltamo et al. 2006, 2007, Packalén & Maltamo 2008), we used mean characteristics and theoretical Weibull distribution series in the simulation.

5.1.2 Standwise field inventory (SWFI)

In practice forest property valuation is usually based on forest inventory data provided by an SWFI. This will gradually change as future ALS inventories become increasingly popular. A_ALS inventories will make forest inventories markedly more efficient than now. Remote sensing will also play a central role in the transition of making forest resource data continuously up-to-date. SWFI was, therefore, chosen as the reference methodology for various ALS inventory methodologies (I-III, V). All in all it can be stated that with respect to stand-level computed NPV, A_ALS inventories result in levels of uncertainty similar or better to those of traditional SWFI. When SWFI uncertainty is compared with ALS inventory uncertainty, it is essential to recognize how stem diameter distributions are formed in the methodologies and what tree- and stand-level characteristics are used by the models simulating stand development (II).

5.1.3 Individual tree detection (ITD) vs area-based ALS inventory (A_ALS)

A clear division between the ITD ALS and A_ALS methodologies has often been made in previous investigations. The greatest advantages of the ITD ALS methodology are its ability to depict the stem distribution more accurately and less need for ground reference data. The most substantial advantage of the A_ALS methodology is, in turn, its ability to utilize inexpensive low-density ALS data. A_ALS inventory results are also easier to integrate into operative forest-planning computations. At least currently, aerial photography is being utilized in both the single-tree and area-based methodologies. Future ALS intensity information may, at least partially, cancel the need for aerial photography.

ITD carried out with high-density (more than 5 pulses per m^2) ALS data has led to more accurate stand-level inventory results than area-based interpretation, especially if theoretical distributions are used to take into account trees obscured in the ALS data (e.g. Maltamo et al. 2004). Due to high acquisition costs, only the area-based methodology has been utilized in practical applications so far. It is also being currently adopted by several Finnish forest organizations.

The setup, however, is not this simple. First of all, high-density ALS data will be available at increasingly lower prices. On the other hand, the first studies carried out indicated that ITD based on low-density ALS data produces results of reasonable accuracy (Kaartinen et al. 2008, Vastaranta et al. 2009a, Yu et al. 2010). Vastaranta et al. (2009a) compared the accuracy of A_ALS and single tree ALS interpretation (ITD) with the Evo study data used in III, showing that ITD accuracy matched that of A_ALS interpretation, given that ITD interpretation results are calibrated to take into account small obscured trees. Since the ALS data used in the study had a low density rate (0.8-1.8 pulses per m^2), the results can be considered as encouraging in respect with ITD.

The resulting issue is in which inventory tasks it is worthwhile to apply ITD instead of the area-based methodology. This issue culminates in the stem distribution formation method applied in forest-planning computations. ITD leads to more accurate results in tasks where accurate stem distributions based on single-tree measurements are required, e.g. in estimation of timber assortment-level stand characteristics. The area-based methodology produces results matching the accuracy of ITD in the case of stand-level mean characteristics. On the other hand, ITD would be required for detailed mensuration of tree growth and input data for various growth and biomass models. Incorporation of ITD with terrestial laser scanning (TLS) and logging machine measurements would pave the way for 'precision forestry' (Holopainen et al. 2010c), in which forest resource monitoring could be carried out at the single-tree level.

Several studies (e.g. Vastaranta et al. 2009a, Yu et al. 2010) have shown that ITD as well as A_ALS interpretation produce significantly biased inventory results for sum characteristics, i.e. basal area and mean stem volume. With respect to individual stand characteristics, e.g. mean stem volume, this bias can be annulled via calibrations based on accurate field measurements. The calibrated results tend to be highly accurate (see e.g. Naesset 2004).

An advantage of the nonparametric methods applied in A_ALS interpretation with respect to regression analysis is that all stock and stand characteristics of interest are estimated simultaneously. With respect to single characteristics, regression analysis usually leads to slightly more accurate results than the nonparametric k-NN methodology (e.g. Vastaranta et al. 2009a). The k-NN methodology was, however, applied in IV, because the purpose of the study was to imitate a practical forest-planning case.

In several studies (e.g. Peuhkurinen et al. 2007, Maltamo et al. 2009, Vastaranta et al. 2009a), allometric models describing the relationships between tree crown size, height and diameter-at-breast-height (DBH) were applied as a part of the ALS ITD methodology. These models are, however, highly sensitive to errors in their input data. The automatic measurement results of tree crown size in particular tend to be error-prone. Thus, estimation of DBH on the basis of tree height and crown size results in a rather notable degree of uncertainty. Nonparametric algorithms applicable to single-tree interpretation are, therefore, currently under development (e.g. Maltamo et al. 2009, Yu et al. 2011) to part with the use of allometric models.

5.1.4 Interpretation of tree species

Tree species interpretation was assumed to be fully successful (I, II). This is not a realistic assumption, since the current accuracy of tree species interpretation under conditions prevalent in Finland (three dominant tree species), using single-tree ALS interpretation ranges from 60% to 90%, depending on pulse density (e.g. Korpela et al. 2010, Vauhkonen et al. 2010). Utilization of aerial photography in association with the ALS data usually improves the interpretation accuracy. In the most recent study Korpela et al. (2010) achieved an accuracy of 88-90% in the classification of Scots pine, Norway spruce and birch, using ALS intensity features.

With respect to A_ALS interpretation, species stratum-level characteristics are estimated at a considerably lower accuracy level than stand-level mean characteristics. The relative RMSE of stratum-level characteristic interpretation ranged from 25% to 80% (Packalen & Maltamo 2006, 2007, Holopainen et al. 2008, Peuhkurinen et al. 2008). It must, however, be noted that the relative RMSE figures do not necessarily depict accuracy reliably when the absolute values of the characteristic in question are relatively small.

We determined the accuracy achievable at the timber assortment level (IV). The ALS inventory led to a relative RMSE error of 24,7% with respect to estimated logging revenue (clear cuttings) when the estimated values were compared with values derived on the basis of logging machine measurement results. At the same time, the relative prediction error of timber assortment level volumes were 33,6% (spruce), 79,2% (pine) and 78,6% (birch) when using A_ALS inventory method. Errors in tree species recognition were probably the cause for the inferior accuracy rates found in estimation of the timber assortment-level characteristics.

5.2 Growth models

Growth model-related uncertainty proved to be the most influential source of error when compared with the uncertainty associated with inventory data and timber price fluctuation (V). This result was probably a consequence of the fact that of all tree- and forest-related models, growth models are the ones that function the most poorly (e.g. Kangas et al. 2003). Development of growth models would therefore also be essential from the standpoint of forest property valuation.

In studies V and VI the uncertainty of growth modelling errors involved only errors in growth models that were divided into intra-stand and inter-stand random variations. A mortality model was not utilized because no well-functioning mortality model for the stand-level models utilized here was available. However, in our case we had well-managed forests, i.e. the missing mortality model was not a large problem. If we would simulate forests that are close to natural development, this would be a more significant problem. The uncertainty of growth modelling in SIMO forest simulations utilized here is described further in Mäkinen et al. (2008, 2010) and Mäkinen (2010).

Mäkinen et al. (2010) applied MC simulation to determine how inventory data errors affected the functioning of forest-planning growth models used in tree- and stand-level simulators during a 30-year-long simulation period. Their study showed that tree-level simulators are less sensitive to inventory data errors than stand-level simulators. Application of single-tree ALS inventory data led fewer errors than the application of traditional SWFI data.

One way to assess stand growth potential is to apply the dominant height-based site-indexing methodology (Holopainen et al. 2009, 2010a). Holopainen et al. (2010a) showed that forest site type could be assessed quite accurately using the A_ALS based site-indexing method, however, practical problems arose from the fact that the success of the procedure is highly dependent on the existence and accuracy of stand age information. One alternative to tackling this problem is to assess tree growth directly, using multitemporal ALS data. Promising results associated with tree growth mensuration (height increment) via single-tree ALS interpretation have already been reported (Yu et al. 2004, Yu 2007). If stand-level volume increment could be estimated with sufficient accuracy, the estimates could subsequently be applied to assess the forest type, if necessary. After all, in forest property valuation the main emphasis is on site productivity, and forest site type would then merely be a side product.

Multitemporal ALS inventory data may also be applied for constructing future growth models or even for directly measuring tree and stand growth. Future laser-based mensuration techniques (TLS, ALS) can be considered as highly potential in this regard, especially from the standpoints of growth model and biomass model construction. Laser mensuration provides a relatively speedy and inexpensive technique for acquiring relatively accurate data required in these model construction processes.

5.3 Timber price

When forestry yield value as well as market-based yield value is computed, the most common way to incorporate timber prices is to apply mean prices based on the realized prices of the past 1-3 years. A more advanced and also complicated approach is to try to predict future timber price development based on realized past price development. Predictions can be carried out using GMR or GBM processes.

Figure 1 depicts the real price development of raw timber in Finland 1986-2009. It can clearly be seen that timber prices tend to revert to certain mean values in all timber assortment types. Significant deviations to each side occur for sure. A clear dependency between saw-wood and pulpwood prices can also be observed. An exception to this dependency is the clear increase between spruce saw-wood and pulpwood prices during the late 1990's. This was probably caused by the abrupt increase in demand for large-dimensioned spruce saw logs to be exported to Japan.

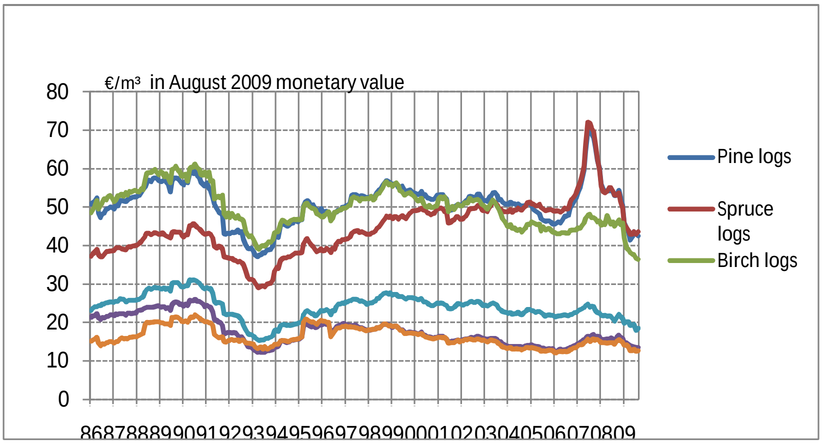

Figure 1. Historical data (1986-2009) on real timber prices as EUR/m^3 (price level of August 2009). Prices deflated using wholesale price index (1949=100).

The results showed timber price fluctuation was not as significant source of uncertainty as inventory data and growth model uncertainty (V, VI). The effect of timber price fluctuation on the variation in stand NPV was 8% only, whereas the uncertainty levels caused by inventory and growth model errors were appr. 30%. The minor impact found for the uncertainty related to timber price fluctuation probably resulted from the study, which applied GMR price models.

In other words, the reverting of timber prices to certain mean values smooths even major momentary fluctuations when stand NPV is computed over lengthy, i.e. rotation over long, periods of time. The significance of timber price fluctuations would probably be greater, provided that price models based on GBM are applied in the computations.

Based on the information in Figure 1 the use of GMR price models is totally founded, but it is unknown if this holds also in the future. When the price model to be applied in the study was chosen, it was assumed that the future demand for raw timber would match that of the past. However, the degree of domestic investments made by Finnish forest companies, have decreased dramatically during recent years. The assumption of continuing raw timber demand made during the study is therefore highly debatable. We also focused solely on traditional timber assortments, which have already begun to include various energy wood assortments. From the viewpoint of the forest owner, the profitability of energy wood utilization is, at least currently, dependent on the state subsidy policy. Energy wood considerations were, therefore, omitted from the study.

The utilization of forest resources will probably undergo future diversification. For example, carbon sinks will probably turn out to be financially beneficial for forest owners in much the same way as the securing of biodiversity via nature value trading is currently. From the standpoint of forest economic value, these new forest values will probably compensate for the diminishing capacity and raw timber demand of various forest industries. However, these new potential forest values were not considered in this study.

5.4 Combined effects

Our objective, apart from individual sources of error, was to also examine entities formed by various sources of error, thus enabling the analysis of various interrelationships (IV, V, VI). These types of analyses have previously not been carried out.

We showed that when errors caused by stem distribution generation, originating from stem form prediction and erroneous inventory data, are simultaneously analysed the error is different than sum of these errors (IV). Similar results were also derived in V and VI, i.e. the joint uncertainty caused by inventory error, growth models and timber price fluctuation is less than the uncertainty sum of the individual sources of error (V, VI).

5.5 Significance of the study from the standpoint of forest property valuation

Uncertainty related to NPV computations was analysed specifically on the basis of current or near-future inventory methodologies, i.e. SWFIs and A_ALS inventories (I, III, IV, V, VI). On the other hand, the study shed light on the benefits to be gained in forest-planning computations, given that functioning single-tree ALS interpretation is applied in the inventory phase (II). The study also focused on how to utilize different types of inventory data in stand-level NPV computations. Emphasis has been on analysing the entire computation process instead of scrutinizing the functioning of individual tree- or stand-level models.

As a consequence of the joint error analyses, the study provided useful information on the mutual relationships of the various sources of uncertainty, i.e. what proportion of the joint uncertainty related to computed stand-level NPV is due to each individual source of uncertainty and what to focus on to decrease the degree of joint uncertainty. For example, we suggested that even though forest inventory data are useful, NPV estimation is still characterized by a remarkable degree of uncertainty that is caused by growth models and fluctuations in timber price (V). In other words, the gains in joint accuracy accomplished by improving inventory accuracy are limited, no matter how much the inventory accuracy is improved. This is relevant to development and application of new inventory methodologies. Development of growth models more accurate than the current ones would be the most efficient way to reduce the uncertainty in NPV computations, although the derivation of absolutely complete stand-level growth models is a more or less impossible task.

Development of a forest property valuation methodology utilizing ALS- and aerial photography-based forest inventory can be considered as a future vision. When timber assortment volumes are estimated, using current inventory methodologies, the degree of uncertainty in stand-level economic value resulting from the inventory is appr. 30% alone (IV, VI). Uncertainty caused by the growth models applied and fluctuation in raw timber prices will increase the relative uncertainty to near 50% in stand-level (V). However, in property level uncertainties are much lower.

These figures are rather significant but the matter can also be scrutinized from another point of view: near-future ALS data will be available for increasingly large areas in Finland. This means that the reference data measured in this study could be used for assessing stand-level forest value even in vast forested areas (e.g. forest centre) at accuracy levels matching the relative accuracy of the timber assortment volumes presented here. The costs of the inventory in question would amount to only a fraction of those resulting from a traditional SWFI.

With respect to current forest property valuation approaches, the study can be seen to provide the following benefits:

Sales comparison approach: Forest resource information, which in practice decide the estate's value, should somehow be included in forest property transactions. In practice this has been accomplished using SWFI, but these types of separate inventories will probably at some point apply ALS inventory methodologies to increasingly greater extent. In other words, the forest resource inventory methodology related uncertainty estimates arrived at in this study are also applicable to forest property values derived by the sales comparison approach. In addition to forest resource accuracy, another source of uncertainty related to this approach is the discovery of relative reference transactions. The study does not provide solutions for this problem.

Summation approach: The study provides insight to the degree of uncertainty included in the Tapio tables (Forestry Development Centre Tapio 2002) applied by the approach. The sapling stand values and thinning stand-expected values presented in the tables are computed using the Motti simulator (Hynynen et al. 2002). The tree- and stand-level models applied in this simulator are also used in the SIMO forest-planning computation system (II, III, IV, V, VI). In other words, the results obtained provide insight to the degree of uncertainty related to estimated sapling and thinning stand values, based on the Tapio tables (V, VI).

Forestry yield value and market-based yield value approaches: A central offering of the study is the methodology developed to determine the uncertainty related to the computation of forestry yield value (NPV). Understanding of the magnitude and the cause- and effect-relationships concerning this uncertainty is highly relevant to developing forest-planning methodologies.

The determination of forest property yield value incorporating the current market would, however, be more appropriate with respect to the standpoint of forest property valuation. In practice this implies that the estimated forestry yield value and related uncertainty estimates should be enhanced by incorporating forest property market values in the valuation process. In Chapter 5.6 two alternative views are presented on how to take estimation process-related uncertainty into account in forest property valuation processes and how to determine forest property yield value, taking the market into account on the basis of estimated forestry yield value.

5.6 Future methodologies for valuating forest property

5.6.1 Association of forest resource information with purchase price registers

On account of forest owner information security forest-planning information cannot be handed over to other parties in Finland. This is a problem from the standpoint of forest property valuation, since the NLS's PPRs do not, therefore, include forest resource information, although digital forest plans stored in geographical information systems (GIS) have been prepared for almost every forest property in Finland. Negotiations on the degree of publicity related to forest-planning information have long been continued, e.g. it has been suggested that timber resource information should be made public and only information related to silviculture of forests be kept private. On the other hand, it has been proposed that forest centres could deliver planning information to third parties according to separate agreements. It is, however, probable that the current situation in which forest owner information security is highly emphasized will continue.

5.6.2 Alternative I: Forest-planning information can be associated with purchase price registers

Continuous updating of forest resource information has already replaced one-off inventories in the managing of state- and forest enterprise-owned forests. This has also been attempted in the management of privately owned forests, along with a new forest-planning system to be introduced in 2010. The most efficient way to solve the PPR-related problem would be to link the purchase price database with the forest resource information-updating systems by which up-to-date forest resource information would be accessible to the NLS, as well as purchase price information to various forest organizations.

Successful updating of forest resource information is dependent on highly accurate inventory data, which in the future will be acquired increasingly by ALS-based methodologies, updating of untreated stand information by forest-planning computational procedures and updating of treated stand information by information gathered by logging machines. The results (I-VI) are directly applicable for judging various sources and magnitudes of uncertainty related to the updating of forest resource information.

5.6.3 Alternative II: Forest-planning information cannot be associated with purchase price registers

The starting point for Alternative II is that forest-planning information cannot be associated with PPRs even at a later date. In this case a separate inventory must be carried out on the estate to be purchased, which could be done at moderate cost by acquiring low-density ALS data and, if necessary, digital aerial photos covering the forested area. Depending on the heterogeneity of the forests, a set of 500-800 field sample plots could be allocated in the area on the basis of remote-sensing prestratification (see Holopainen et al. 2008). The plots could then be measured accurately on a stem-by-stem basis. Timber assortment volumes could next be determined as in IV and sites indexed as in Holopainen et al. (2010a).

The costs of a separate inventory are highly dependent on the size of the forested area. If the size of the area were to exceed 10 000 ha, the costs of the inventory method would probably be less than 5 €/ha. The costs can be greatly reduced, using existing field sample plot data as reference data. Information gathered by logging machines could also be applied for this purpose. The main problem related to the methodology is that it results in a one-off inventory only. Since forests change over time, the inventory data should be updated.

5.6.4 From forestry yield value to market value

Whatever the degree will be of forest-planning information publicity, it is unrealistic to assume that PPRs would always have up-to-date information on the estate in question and that there would always be a sufficient amount of appropriate reference transactions. Thus one way to combine the forestry yield value approach with the market-based yield value approach would be to carry out on an annual basis separate inventories on all (or on a major sample) of the estates targeted for purchase. The sampled data could then be used to construct economic models for depicting the development of purchase prices. The models derived could be applied to predict the market value of any forest property and the value estimates could be supplied with confidence ranges depicting the degree of related uncertainty. However, the problem would then still be that the models would reflect the realized situation and not necessarily future development.

5.7 Study limitations

It must be noted that the results derived are more or less dependent on the material utilized in the studies; e.g. forest compartment size and heterogeneity influence ALS inventory accuracy (I-VI). The results concerning timber assortment-level inventory accuracy (IV) were slightly poorer than those obtained in other respective studies carried out in eastern Finland (Packalén & Maltamo 2008, Packalén 2009), probably due to the smaller compartment size and greater heterogeneity in the Evo study area.

The results are also strongly dependent on the algorithms and methodologies applied. There are notable differences in the accuracy of SWFIs between different regions (and planners), but this also applies to ALS inventories. For example, the best ITD algorithm was chosen (II) from the 11 algorithms investigated in the EUROSDR research project (Kaartinen & Hyyppä 2008). The research report showed that the accuracy of the algorithms investigated varied widely. The results derived would thus have been poorer with respect to ITD had an inferior algorithm been chosen (II).

The research material applied (I) was acquired from city forests, whereas the field reference data applied in the other studies were acquired from commercial forests. Our study areas were, however, all located in southern Finland. Generalization of the study results to the whole of Finland without carrying out additional investigations would therefore not be recommended.

It must also be noted that ALS data quality and inventory methodologies are evolving at a significant tempo. High-density ALS data will probably be available in a few years at the same price as low-density ALS data are now and that the price of the latter will be even more inexpensive than it is currently.

In examining the results, it would be better to focus on the relative accuracy and interrelationships of the methods used than on the absolute values in euros.

Many assumptions and simplifications had to be made during the course of the separate studies V and VI. The effects of stem quality, special timber assortments and energy wood on logging revenue were not taken into account. It was also assumed that stands were treated according to the traditional low-thinning regimes (Forestry Development Centre Tapio 2006). All of these factors affect forest NPVs. However, their influence on the importance sources studied is probably not that significant. In addition, natural risk factors such as wind, snow, fire, insect and fungi damages were not taken into account. It would, in principle, be possible to also consider forest damage risks as uncertainty sources in forest NPV computations, given that models for predicting the effect of various damage factors on stock growth were available (see e.g. Forsell et al. 2009).

5.8 Future research

All Finnish forest organizations (also those dealing with privately owned forests) will base forest-planning on the continuous updating of forest resource information. A crucial issue involves not only the accuracy of the updated data, but also that of the actual updating procedures. Future forest resource data updating can be enhanced by applying either multitemporal ALS inventories or combinations of ALS inventories and logging machine mensurations (e.g Melkas et al. 2009).

ALS is carried out at relatively low altitudes, which consequently makes it relatively expensive per unit area. Other remotely sensed data will still be needed, especially when updated information is required. Holopainen et al. (2010b) compared the accuracy of low-pulse ALS data, multi-temporal high-resolution noninterferometric TerraSAR-X radar data and a combined feature set derived from these data in the estimation of forest variables at the plot level. The ALS data were superior to the TerraSAR-X data, but some TerraSAR-X features were incorporated into the combined feature set. Holopainen et al. (2010b) concluded, however, that due to favourable temporal resolution, satellite-borne radar imaging is a promising data source for updating large-area forest inventories based on low-pulse ALS, i.e. utilization of high-resolution radar images in updating forest resource data should be further studied.

Forest property valuation may require inventories in addition to those carried out for forest-planning purposes. It should then be acknowledged what kind of information is required for which purpose; e.g. if accurate stem distribution information is required, development of single-tree ALS interpretation would be the key (essential). One future research topic should be the development of combined ALS methodologies in which large, clearly distinct trees would be interpreted on a single-tree basis and the rest of the stock on an area basis. The simplest way to implement such a methodology would be to first prestratify the stock (compartments) by development class, after which compartments having moderately dense stocks belonging to advanced development classes would be subject to single-tree interpretation and the rest to area-based interpretation. Sapling stands will probably also have to be assessed in the field, since ALS interpretation does not function well in these cases, while most silviculturally important treatments are carried out during the stand's seedling and sapling stages.

ALS-based sampling could also be applied in separate inventories (e.g. Holopainen & Hyyppä 2003). ALS would be an excellent tool for strip-sampling purposes. In a large forested area, a sample size of 5% of the total area would probably be enough for acquiring sufficient stand- or property-level forest resource data. Digital aerial photos or high-resolution optical or microwave satellite images could be utilized for generalization of the laser sample at the stand or plot level. If existing field sample plot data were made available for reference data purposes, sampling would be a highly advantageous and inexpensive methodology, providing forest resource information on vast forested areas.

One interesting future issue will be the ensurement of ALS inventory quality. The quality and amount of field reference data as well as the stand structure of the forested area to be inventoried have a profound influence on the quality of the ALS interpretation. There are also differences between the ALS instruments applied, the influence of which is currently unknown. The selection of ALS features to be used in the interpretation is a significant issue with respect to interpretation accuracy. The quality of an ALS inventory undertaken should therefore be evaluated at the forest centre level. One method for quality control would be the utilization of ITD ALS interpretation, given that it would yield clearly more accurate interpretation results than the currently applied area-based methodology.

Our studies (III-VI) were based on operative inventory methodologies currently in use, the future accuracy of which will probably increase significantly. When nonparametric ALS interpretation is applied, the resulting accuracy is highly dependent on the amount and accuracy of the field data used for reference purposes. If some tree species or development class stratum lacks field reference data, the respective interpretation accuracy will also be inferior. The influence of the amount and quality of field reference data on ALS interpretation accuracy should therefore be clarified in follow-up studies.

Stand size and homogeneity have a decisive influence on interpretation accuracy. For example, Hyyppä et al. (2000) showed that stand size significantly affects remote-sensing interpretation accuracy. In addition to inventory area size, other research topics relevant to ALS inventory quality include the development of tree species recognition as a part of ITD ALS inventory, selection of ALS features and the utilization of full-waveform laser scanning.

In addition to timber assortment quantity and value, site productivity has a decisive impact on the forestry yield value of a forested property. One way to determine site productivity in advanced single species (more than 60% of the stand's stock is made up of a single tree species) is to apply dominant height-based site indexing. Both the A_ALS and ITD inventory methods function best at estimating height parameters.

Holopainen et al. (2009, 2010a) developed a practical ALS-based methodology to determine site productiveness. They compared various methodologies to determine dominant height, using ALS data, and verified ALS-based site indexing as a means to assess forest site type, using models derived for artificial and natural stands. The A_ALS method was used to estimate dominant height with the nonparametric k-NN method, or, for comparison, directly from the height distribution of the ALS pulses. The ALS-based methodology was compared with site indexing, based on field measurements. Field reference data were acquired from 102 plots measured in the Evo area, for which the forest type was determined in the field. Successful site indexing is dependent on the accuracy of dominant height and mean age estimation. Since the objective of the research was to develop practical methodology, age information was adopted from the respective forest management plan. Holopainen et al. (2010a) showed that A_ALS site indexing functioned in advanced single-species stands quite well. The forest site type was classified correctly at a rate of 70%; however, the methodology is highly sensitive to errors in mean age determination, especially in the case of site-indexing models derived for artificial stands. Thus, dominant height site-indexing models should be developed to better support ALS inventories.

It would be worthwhile to follow up the site indexing-related research initiated by Holopainen et al. (2009, 2010a) to lessen the dependency of height-based indexing on stand age. As an alternative to height-based indexing, an approach in which site productiveness is assessed directly via growth estimation carried out by multitemporal ALS inventorying should be investigated. In addition to ALS inventorying, the site index could also be assessed, utilizing other geospatial data. The intrastand variation in stand productiveness should be analysed, using the ALS site-indexing methodologies already or still to be developed, including those used in forest-planning computations and silvicultural treatments.

The methodologies developed (IV, V, VI) should be tested in larger study areas and in other than the southern parts of Finland. Combining the forestry yield value approach with the market-based yield value approach visualized in the study summary should also be investigated with real data that can be linked with market prices of forest properties (PPR). The influence of forest ownership type (forest owner's attitude to risk) on the outcome of forestry yield value computations and the degree of various sources of uncertainty will also be analysed in follow-up studies, as well as the effects of various timber price models on the degree of timber price-related uncertainty.

Valuation and incorporation of bioenergy and other forest resources such as scenery, biodiversity and carbon absorption in the uncertainty computations present major challenges for future studies. The increase in forest damage risk caused by climatic change should also be taken into account. Follow-up studies should therefore be carried out to determine how various forest damage types influence tree growth and stand-level forestry yield value. Further studies should also account for the uncertainty in silvicultural costs.

It should be pointed out that from the forest property valuation point of view, the results of the thesis can be seen as preliminary; several assumptions were made and many aspects and methodologies that are relevant to forest property value estimation are missing. Stochastic optimization, using scenarios that Pukkala (1997, 2005) and Eriksson (2006) utilized, is one of these. In future studies spatial optimization could be utilized and heuristic optimization (simulated annealing, tabu search, genetic algorithms, Hero) used to tackle non-linear or spatial problems that are unfeasible for linear programming should be examined.

6. Conclusions

Our results show that forest inventory (SWFI, ALS-based inventories) errors led to significant mistiming of simulated loggings and subsequent losses in simulated NPV. Forest inventory methodologies, growth models applied in forest-planning simulation computations and fluctuation in timber prices cause significant uncertainty in the computation of stand-level and property-level forestry yield value (NPV). At the stand level, the uncertainty resulting from A_ALS inventory methodology and growth model functioning is greater than that caused by timber price fluctuation, given that future timber price fluctuation will be predicted with a GMR price model.

At the forest property-level, A_ALS inventory errors were the most prominent source of uncertainty. The uncertainties related to A_ALS inventory errors, growth models and timber price fluctuations were remarkably lower than stand-level uncertainties. However, A_ALS inventory led to significant biases at the property level, probably due to ALS inventories that tended to overestimate young stand timber volumes and underestimate developed and mature stand timber volumes. Bias in developed and mature stands has more significant impact on euro-based NPVs than bias in young stands.

With respect to forest inventory methodology, uncertainty results in addition to the actual inventory error by generation of stem distribution, prediction of stem form and simulation of bucking. A_ALS inventorying results in similar or lesser degrees of uncertainty in computed stand-level NPV than traditional SWFI. Single-tree (individual tree detection, ITD) ALS inventorying may result in more accurate stem distributions than the application of A_ALS inventorying. This also leads to more accurate timber assortment volume estimates and consequently to lower levels of inventory-related uncertainty. However, current single-tree ALS inventory algorithms require further development in automatic location of trees and automatic tree species recognition.

In the present study, a foundation for developing a practical methodology for valuating forested properties in which final value estimates can be supplied with statistics depicting the degree of related uncertainty was established. Study also furthered the development of a forest property valuation methodology totally based on ALS inventorying. Our results can also be applied to assess the accuracy of continuous forest resource updating and its related uncertainty.

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The economic value of forests is crucial information for landowners and various forestry organizations. One method of deriving the economic value of a forest stand or property is to calculate the difference between the present values (net present value, NPV) of all future expected revenues and expenses. However, the NPV of forested land is subject to various uncertainties. These include errors in the forest inventory data, growth and yield models used in the simulators, development of timber prices and the rate of interest. During the past 10 years, 3D methodologies based on small footprint airborne laser scanning (ALS) have experienced a major technological leap in forest inventory and management planning. The present study forms a basis for developing practical methodologies for taking uncertainty into account in ALS-based management planning and forest valuation. The importance of various sources of uncertainty is revealed and a concept of what to focus on to reduce uncertainty is provided.

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