The updating of forest resource data for management planning for privately owned forests in Finland.

Pekka Hyvönen
Faculty of Forestry
University of Joensuu

Academic Dissertation

To be presented, with the permission of the Faculty of Forestry, University of Joensuu, for public criticism in Auditorium Käpy of the Finnish Forest Research Institute, Yliopistokatu 6, Joensuu, on 25th May 2007, at 12 o'clock noon.

2

ABSTRACT

In Finland, the forest resource data for management planning is traditionally collected by periodic standwise field inventories, which are usually carried-out over different regions during 10–15 year intervals. The data is used for the compilation of management plans for forest estates. Between inventories the plan and the original stand data can be used, e.g., in the operational planning of timber sales and silvicultural treatments. In operational planning, up-to-date stand data are needed. Therefore, interest in the cost-efficient methods for the updating has increased in recent years.

The aim of this thesis was to test potential methods for the updating of forest resource data for management planning in private forestry in Finland. The main criterion in the selection of the studied methods was that they can be applied to the current planning system of Regional Forest Centres, with moderate modifications. Three methods were tested: a) an automatic interpretation of remote sensing material utilising nonparametric estimation at stand- and at segment-levels, b) follow-up of changed stands and c) change detection at stand-level.

The estimations based on the use of medium resolution satellite images at the stand-level and high resolution aerial photographs at the segment-level did not achieve the defined accuracy level of stand attributes and treatment proposals. Estimates based on these methods can be utilised for obtaining approximate information on the stand attributes. The estimation method at the segment-level was considered to be worth of further research.

The follow-up of changed stands proved to be a potential method for updating forest data. The information for 75% of the management operations was found from the data bases of the Regional Forestry Centre and the Forest Management Association. An updated forest management plan was composed based on new inventory data on changed stands and computationally updated data on unchanged stands. The reliability of the updated plan was equal to that composed based only on new inventory data. The tested change detection with bi-temporal aerial photographs should play a part in the updating procedure. The overall accuracy of change detection was 84.7% at best, and 84.2% of the thinned stands were found.

According to the results of this thesis, the follow-up of changes combined with change detection with remote sensing is a promising method for the updating of forest resource data in privately owned forests.

Keywords: standwise inventory, updating, stand attributes, nonparametric methods, change detection, segment.

ACKNOWLEDGEMENTS

Joensuu, May 2007

Pekka Hyvönen

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following articles and manuscripts, which are referred to in the text by their Roman numerals I-V. The published articles are reprinted here with the kind permission of the publishers.

I   Hyvönen, P. 2002. Kuvioittaisten puustotunnusten ja toimenpide-ehdotusten estimointi k-lähimmän naapurin menetelmällä Landsat TM -satelliittikuvan, vanhan inventointitiedon ja kuviotason tukiaineiston avulla. Metsätieteen aikakauskirja 3/2002: 363–379.

II   Hyvönen, P., Pekkarinen, A. & Tuominen, S. 2005. Segment-level stand inventory for forest management. Scandinavian Journal of Forest Research 20(1): 75–84.

III Hyvönen, P., Pekkarinen, A. & Tuominen, S. 2007. Ilmakuvasegmentteihin perustuvan kaksivaiheisen otannan luotettavuus puustotunnusten ei-parametrisessa estimoinnissa. Metsätieteen aikakauskirja 1/2007: 39–53.

IV   Hyvönen, P. & Korhonen, K.T. 2003. Metsävaratiedon jatkuva ajantasaistus yksityismetsissä. Metsätieteen aikakauskirja 2/2003: 83–96.

V   Hyvönen, P. & Anttila, P. 2006. Change detection in boreal forests using bi-temporal aerial photographs. Silva Fennica 40(2): 303–314.

AUTHOR'S CONTRIBUTION

In study I, Pekka Hyvönen made all the calculations, analysed the results and wrote the article. Anssi Pekkarinen provided the algorithms for the segmentation and designed and implemented algorithms for the k-NN estimations.

   In study II, Pekka Hyvönen arranged the fieldwork, made segment-level estimations, analysed the results and wrote the first draft of the manuscript. Sakari Tuominen did the plot-level estimations. Anssi Pekkarinen designed and implemented the algorithms for the segmentation and k-NN estimations. All contributed to the writing up of the final article.

   In study III, Pekka Hyvönen arranged the fieldwork, made estimations and simulations of sampling, analysed the results and wrote the first draft of the manuscript. Sakari Tuominen did the image radiometric correction and Anssi Pekkarinen provided the algorithms for the segmentation, clustering and k-NN estimations. All contributed to the writing up of the final article.

   In study IV, Pekka Hyvönen was responsible for the fieldwork, mainly for the calculations, and analysis of the results. Kari T. Korhonen planned the research and made the calculations with the stand check data. Both contributed to the writing up of the article.

   In study V, Pekka Hyvönen obtained the data. Perttu Anttila analysed the effect of the stand properties on the change detection. Both contributed to other calculations, analysis of the results and the writing up of the article.

CONTENTS

1 INTRODUCTION

1.1 Forest inventory for management planning for private forests in Finland

The forestry land area of Finland is about 26.3 million hectares of which 13.7 Mha (52.2%) are owned by non-industrial private forest (NIPF) owners (Finnish statistical… 2006). The private forest's proportion of the forest land is even more; 59.6%. Furthermore; their proportion of the growing stock is approximately 64.2% and their proportion of the commercial cuttings are approximately 85.8%. Consequently, forest management planning for private forests is important for the Finnish forest sector.

Up-to-date forest resource data are needed for forest management planning. In Finland, there are basically two different inventory systems. Since 1921, the national forest inventory (NFI) has produced statistical information about forest resources at national and regional levels (Ilvessalo 1927). The first NFI was based on line-wise survey sampling (Ilvessalo 1927). Over the years, the sampling design and measurements have been changed to meet the varying requirements. The present NFI is based on clusterwise systematic sampling and it covers all land area and owner groups. The inventory cycle has been about 8–10 years. The 10th NFI (NFI10) started in year 2004. The inventory cycle was shortened to 5 years. The Regional Forestry Centres (RFC) carry-out a part of the field work in NFI10.

The second inventory system is designed for management planning. It is mainly carried-out by the RFC and partly funded by the government for private forests, by Metsähallitus for state-owned forests and by forest companies for their own forests. In private forests, the RFC has organised the inventory periodically in regions. The size of a region normally varies between 2 000–6 000 hectares. Thus, one or two surveyors are able to do the fieldwork for the region during one field period. The cycle of these inventories in private forests has been approximately 10–15 years.

In Finland, the data for forest management planning is traditionally collected by standwise field inventories (e.g. Poso 1983). The first standwise inventories began in the state-owned forests in 1907 (Lihtonen 1959). Delineation of the stand boundaries was at that time based on a land survey and later on existing base maps and aerial photographs. The utilisation of aerial photographs in forest inventory started, in practise, in the 1920s (Sarvas 1938, Lihtonen 1959, Nyyssönen 1959) and they were first used only for mapping purposes. The assessment of volume of growing stock was still based on visual estimation of stand density and a tree height measurement, both done in the field (Ilvessalo 1965). The use of aerial photographs increased after World War II, after an increase in use of infrared films. In addition to delineation of stand boundaries, the aerial photographs were also tested for their use in the estimation of growing stock (Nyyssönen 1955). Moreover, the relascope was invented in 1947 (Bitterlich 1948, Loetsch and Haller 1973) and the method of sample based forest inventory at stand-level became common. In the 1970s, aerial photographs were also utilised for stand delineation in the RFCs (at that time known as Regional Forestry Board) (Jaakkola 1979).

The first "computerised database" used by the RFCs was the so-called MTS-ALUE/ATK-system, between years 1974–1987. After that came the first implementation of the fully computerised planning system called TASO, between years 1988–1998. TASO included the NALLE mapping system. In the TASO system, the stand attributes were assessed for the whole stand and stored in the database; the attributes of the tree species

were not stored separately (e.g. Ranta 1991, Taso. Maastotyöopas 1993, Oksanen-Peltola 1999b). At the end of 1990s, a new inventory/ planning system Solmu, later referred to as Luotsi, was introduced (e.g. Oksanen-Peltola 1999b). This system is in present use in the RFCs.

The data collection for Luotsi (databases) is based on the Solmu inventory system (Solmu. Metsäsuunnittelun… 2006). The inventory system consists of several phases. Before fieldwork, stand boundaries are delineated on aerial photographs, which are typically digitised colour-infrared (CIR) photographs at a scale of 1:30 000. Stand boundaries are corrected, if needed, during a fieldcheck. The average stand size in southern Finland is approximately 1.5 ha, and stands under 0.5 ha are not usually identified.

A stand is considered to be homogeneous in respect to e.g. soil and growing stock (Davis and Johnson 1987). Consequently, the stand is a basic treatment unit in silviculture. According to e.g. Poso (1983), the inventory system for forest management planning in Finland is a compartmentwise inventory rather than a standwise or stand-level inventory. Forest compartments are delineated as rational management units, as is the practice in inventory in Finland. Thus, a compartment can include small areas that differ from the average values of the compartment. Therefore, variation within a compartment may be high. According to Koivuniemi (2003), the delineation of compartments should be part of actual forest management planning, and the delineation of stands should be part of forest inventory. In this study (and in sub-studies), the terms stand and compartment mean the same. In addition to stand and compartment is a micro- or sub-stand. It is usually a part of the stand and thus, smaller than the management unit. As these micro-stands are created by image segmentation algorithms, they are usually referred to as segments.

Basic data and characteristics for the stand are assessed in the field using subjectively placed sample plots. The sample plots are usually relascope plots (Bitterlich 1984) in thinning and mature stands, and circular plots in seedling stands. Each tree species and tree storey is described by mean values of age and diameter at breast height, basal area, height and the proportion of saw log (Solmu. Metsäsuunnittelun… 2006). The attributes are estimated for the basal area median tree. In young stands, instead of basal area, the number of stems is estimated. Although several sample plots are measured in one stand, only one mean value is currently stored in Luotsi databases for each variable in a stand. Other characteristics, such as volume of growing stock or other attributes not measured are estimated by applying a chain of models to individual trees, derived from theoretical diameter distributions (e.g. Kilkki et. al. 1989, Kangas and Maltamo 2000b, Maltamo et al. 2002, Redsven et al. 2002).

In addition to measurable attributes, the forest surveyor defines, in principle, cutting and silvicultural management proposals for the next ten years. Proposals are based on stand's initial state and on forest owner's goals. These proposals could be generated by the stand simulator in the planning system based on tree and stand attributes and forest owner's overall or standwise goals when information is available, but in practice these are often decided in the field. In some cases, the forest owner is with the surveyor in the field and makes his/her own suggestions for coming proposals for the stand. After the fieldwork, all gathered data is stored in databases and the forest management plan is composed. In principle, the present system enables, to some extent, an updating of forest data to support operational planning between periodic inventories. In practise, data is not kept up-to-date after silvicultural or cutting operations. Thus, great proportions of data are outdated due to the high utilisation level of the forest. In practical forest management, fully up-to-date stand data is important (e.g..Paananen and Uuttera 2004).

In recent years, approximately 1.0 Mha of the privately owned forest is inventoried annually by RFCs and approximately 0.1 Mha by Forest Management Associations (FMA) (Tapion vuositilastot 2005, Uuttera et al. 2006). The costs of the field work varies in different parts of Finland, but on average the costs in 2004 were approximately 9.2 €/ha (Uuttera et al. 2006) and the total inventory costs were 17.3 €/ha. As the government subsidises the data collection, forest owners pay only 5–10 €/ha of the forest management plan.

On average, 60% of NIPF owners (ha) had valid, in other words less than 10 years old, forest management plans in 2005 (Tapion vuositilastot 2005). As the NIPF has an important role in Finland, many other related organisations have interest in gathered information. In addition to forest owners and RFCs, FMAs, the Ministry of Agriculture and Forestry (MAF), the forest industry and municipalities utilise information collected in regional forest inventories (Oksanen-Peltola 1999a, Paananen and Uuttera 2003). The MAF wants to increase the share of valid plans to 75% of the private forests area and, at the same time, keep the financial subsidy at the same level or even decrease it (Kansallinen metsäohjelma 2010 1999, 2003). In this context, it is obvious that a new more effective planning system and more cost-efficient inventory systems to support it, are needed.

The data gathered in the Solmu inventory system is detailed, each tree species and tree storey is described by mean values. Detailed information enables the use of sophisticated software tools to predict the current and future forest resources (e.g. Eid 1990, Jonsson et al. 1993, Siitonen 1993). The reliability of the predictions strongly depends on forest data: the more accurate the data the better the predictions. Subject to, naturally, the fact that relevant models are used. In practise, the accuracy of stand attributes is dependent on the surveyor and therefore the data has great variation in accuracy. For example, Haara and Korhonen (2004b) reported relative RMSEs at stand-level for basal area 19.6%, height 15.7%, diameter 12.6% and total volume 24.8%, respectively. By different strata the RMSEs were considerably higher.

Although the present Solmu/Luotsi system is considered to be expensive, partly due to the periodic field work, it cannot provide sufficiently up-to-date data for forest management. According to recent studies (e.g. Paananen & Uuttera 2003, Haara & Korhonen 2004a, Anttila 2005, Packalén 2006, Uuttera et al. 2006), the possible methods for the follow-up and updating of forest resources between periodic field inventories are: estimation of forest attributes with remote sensing material, combination of field inventory and remote sensing material, and the follow-up of changes.

1.2 Potential methods for updating forest resource

1.2.1   Methods based on remote sensing

Aerial photographs were first used in Finland for forest mapping and delineation of stand's boundaries (Nyyssönen 1955, Lihtonen 1959, Ilvessalo 1965). In addition to stand delineation, the aerial photographs have shown great potential in the support of manual and numerical interpretation of forest attributes. The first methods that were purely manual aimed at estimating the total volume (e.g. Nyyssönen 1955 and 1959, Eid and Næsset 1998) or, in addition, other stand characteristics, such as tree heights (e.g. Kovats 1997). One important application for which visual interpretation has been utilised, in Finland and in other countries, is two-phase sampling (e.g. Poso 1972, Mattila 1985, Spencer and Hall

1988). In this method, the first phase sample is drawn from aerial photographs. In the second phase, a subset of the samples are measured in the field and the results are generalised to the rest of the samples and thus, to the whole area.

For the Solmu/Luotsi system, the so-called VISU method was developed by Anttila (2002a, 2003, 2005). In this system, old stand boundaries are corrected with the help of new aerial photographs and the old inventory data is updated to the day of examination with growth models of a stand simulator. After this, the photo interpreter compares the new image and updated forest data and determines which stands have been operated after the original field inventory, which not and whether the updated data is correct in those un-operated stands. Then the interpreted operations are simulated into the old data and again subjectively compared to the image if the simulation result is acceptable. Stands for which updated information is accepted are stored in data bases and the rest are checked in the field. In comparison to the standard periodic inventory system, the productivity of the VISU method was 2–4 times higher, varying between 9.9–21.4 ha/h and the RMSE of the total volume varied between 19–51% and the bias between -13.7–4.6%. For tree species, the errors were clearly bigger. The accuracy of this method, as with any manual interpretation methods, mostly depends on the skills of the interpreter, of course. Thus, interest has turned to more automated methods.

Digital image material (digitised from film or digital by origin) has enabled the numerical interpretation and estimation of forest characteristics and thus, more automated methods are studied. The interest in inventories for management planning has mainly focused on very high spatial resolution (VHR) images, e.g. aerial photographs and images of airborne scanners like AISA and CASI, and on medium spatial resolution (MR) satellite images, like Landsat TM images. There are also some studies (e.g. Goward et al. 2003, Peuhkurinen 2005) that have used high spatial resolution (HR) satellite images, like IKONOS.

Irrespective of image category, there are some basic elements to be noticed when these images are utilised (e.g. Campbell 1987, Holopainen 1998, Lillesand et al. 2004). First, the imagery must be corrected, radiometrically and geometrically. The radiometric corrections especially concern VHR images taken from low altitudes, like aerial photographs. In VHR images, there are several factors that affect spectral features and thereby pixel values. Light fall-off effects, variation in atmosphere and even the film type and processing of the film cause variations in the pixel values. Perhaps the most difficult effect to control is the bidirectional reflectance effect caused by the imaging geometry. This can be noticed within the image in the form of variation in brightness in different parts of the image. This is caused by the fact that objects on the image expose either their shady sides or their illuminated sides to the camera depending on their locations on the image (e.g. Holopainen and Wang 1998, Leblanc et al. 1999). Thus, similar objects may have different spectral values and therefore look different in different parts of the image and in different images.

The effects of bidirectional reflectance can be modelled via the bidirectional reflectance distribution function (BRDF) (e.g. Fournier et al. 1995). There are several studies concerning this radiometric correction. Those dealing with physical modelling are very complex (e.g. Nilson and Kuusk 1989, Leblanc et al. 1999, Pellikka et al. 2000) and they require a lot of information on the target. In addition, the empirical calibration models that are used (e.g. King 1991, Holopainen and Lukkarinen 1994) and the image channel ratios (e.g. Hyppänen 1999, Jackson et al. 1990) have been shown to have disadvantages when forest is concerned. Thus, either physical or empirical methods are not used in practice. The more straightforward and simple method, which can be used also on larger scales (e.g.

Maltamo et al. 2006, Packalén 2006), was introduced by Tuominen and Pekkarinen (2004). They tested local radiometric correction with the help of Landsat imagery, which is less affected by the bidirectional reflectance effect than aerial photographs.

The second stage in numerical interpretation is feature extraction; which features should one use and what is the feature extraction unit. The most commonly used are spectral features based on pixel tone values. These can be calculated in VHR images from tree- or sample plot-level to stand-level, depending on the matter of interest. In the case of HR images, feature extraction at tree-level is unfeasible, so the smallest unit is a segment. Another commonly used feature is texture, which describes the spatial distribution of pixel values within an image. The most used texture is probably statistical methods. First order statistics include individual pixels properties, such as a variance of pixel values or variogram (e.g. St-Onge and Cavayas 1995, Wang et al. 1998). The second order (or higher) statistics incorporate interactions between pixel values occurring at specific locations relative to each other (e.g. Ojala and Pietikäinen 2001). The most commonly used statistical method in remote sensing and forest inventory applications was introduced by Haralick et al. (1973). This method relies on a grey-tone spatial co-occurrence matrix, from which the texture measures are derived. Another well-known statistical method is grey level differences (Weszka et al. 1976) which has had many modifications later on.

With MR satellite images, spectral features might produce the best estimation results (e.g. Cohen and Spies 1992, Shang and Waite 1991) whereas texture features have been shown to have advantages with VHR images, such as aerial photographs (e.g. Wang et al. 1998, Franklin et al. 2000, Tuominen and Pekkarinen 2005).

The third stage in numerical interpretation is to obtain the reference data and carry-out the actual estimations. The reference data should be as correct as possible and have large variation in respect to forest attributes. It could be measured in the field or collected some other way, e.g. from databases (Anttila 2002b) or from so called "stembanks", where data is collected from cuttings by a harvester (e.g. Malinen et al. 2001, Rasinmäki and Melkas 2005). The reference data should also be in some relation to the estimation unit. If the target unit is a segment, the reference data gathered by stands might not guarantee the best results.

The nonparametric regression methods, e.g. k-nearest neighbour (k-NN), have been recently, perhaps, the most-used methods in the estimation of forest attributes and also, to some extent, in change detection methods (e.g. Kilkki and Päivinen 1987, Tomppo 1992, Tokola et al. 1996, Varjo 1996 and 1997, Franco-Lopez et al. 2001). Consequently, the use of linear regression models has diminished. The preference for the nonparametric methods is based on their flexibility and ability to describe nonlinear dependences (e.g. Altman 1992, Mouer and Stage 1995), as is often the situation in remotely sensed data. However, the successful use of nonparametric methods needs representative reference data, as the estimates can not been extrapolated. As the k-NN method enables the simultaneous estimation of several attributes, the relationships between estimated attributes are retained and, thus, estimates are realistic (e.g. Härdle 1989). However, it must be noted that the estimates can be highly biased if the reference data does not correspond to the target area. In the nonparametric regression method, the value for the estimate attribute (dependent) is defined with the value of the reference attribute (independent) closest to each other in respect to used features and the number of neighbours (e.g. Härdle 1989, Altman 1992). The value for the estimate can be calculated based on one or several neighbours and their distances can be used as weights. Several weighting functions have been developed (e.g. Wilson and Martinez 1997) but, e.g., Atkeson et al. (1997) have concluded that the different weight functions do not necessarily have great differences in estimations. A widely used

method is weighted Euclidean distance, where the neighbours are usually determined by the inverse squared Euclidean distance. This is used to decrease the bias of the estimates (Altman 1992). Some other weighting methods are, e.g., Mahalanobis distance, which can be calculated from the covariance matrix of the independent variables, and the Most Similar Neighbour (MSN) distance function (Mouer and Stage 1995), which utilises canonical correlations and thus, the size of the weighting matrix can be reduced.

Finally, the reliability of the estimates, and, thus, the estimation procedure, must be assessed. Generally, the accuracy of the estimates is measured with RMSE and precision with bias in the case of continuous attributes and with a confusion matrix in the case of categorical attributes (e.g Loetsch et al. 1973, Campbell 1987, Stehman and Czaplewski 1998, Foody 2002).

Automatic or semiautomatic forest inventory methods have been tested at the stand-level (e.g. Trotter and Dymond 1997, Kilpeläinen and Tokola 1999, Holmgren et al. 1997 and 2000, Hyyppä et al. 2000, Muinonen et al. 2001, Anttila 2002b, Tuominen et al. 2003), at the segment-level (e.g. Mäkelä and Pekkarinen 2001), and at the sample plot-level (e.g. Tokola et al. 1996, Mäkelä and Pekkarinen 2001). In recent years, many studies with VHR images have discussed forest inventory at the tree-level (e.g. Bolduc et al. 1999, Anttila and Lehikoinen 2002, Haara and Haarala 2002, Gougeon 1995, Korpela 2004, Korpela and Anttila 2004, Korpela and Tokola 2006, Leckie et al. 2005, Korpela et al. 2006). In these studies, individual trees or tree tops are usually identified and tree crowns segmented with segmentation algorithms (e.g. Bolduc et al. 1999, Pitkänen 2001, Wang et al. 2004). As the crown diameter and tree diameter at 1.3 m (dbh) are correlated (Ilvessalo 1950), the dbh can be predicted with the help of crown diameter (e.g. Kalliovirta and Tokola 2005) and the height with the help of dbh and, thus, the individual tree volume can be estimated using taper curve models (Laasasenaho 1982).

In studies dealing with inventory with VHR and MR images, the accuracies of estimated forest attributes have been, in general, poorer than that in field inventory. In addition, the remote sensing methods have not been able to produce forest attributes for all tree storeys. Usually dominant and co-dominant trees dominate the estimation procedure and information for dominated trees and the understory can not been estimated. As these smaller trees might have an affect e.g. for silvicultural proposals, they must be assessed in some way. One solution is to utilise diameter distribution models for the estimation of the number and size of smaller trees (e.g. Maltamo et al. 2003).

Whereas the accuracies of the estimates have not been satisfactory, the VHR and MR images have been successfully used for change detections and classifications (e.g. Singh 1989, Häme 1991, Olsson 1994, Varjo 1996, Hyppänen 1999, Haapanen and Pekkarinen 2000, Saksa et al. 2003, Heikkonen and Varjo 2004). The detection of radical changes, such as clear cuts (in Finnish conditions), has been reliable. Meanwhile, the detection of moderate changes has been unreliable, especially in mature stands. The reason for this is that moderate changes only cause minor changes in spectral reflectance (e.g. Olsson 1994, Holmgren and Thuresson 1998).

As the numerical interpretation utilising aerial photographs and satellite images has not been able to produce reliable tree species level estimates, considerable effort has been directed towards airborne laser scanning (ALS). For the last 10 years the research in this area has been lively and the results in estimating the main forest attributes have been promising (e.g. Holmgren 2004, Næsset et al. 2004). The two methods for estimating with ALS data are the canopy height distribution approach (e.g. Næsset 1997a, 1997b, Næsset and Gobakken 2005) and the single tree approach (e.g. Hyyppä and Inkinen 1999, Maltamo

et al. 2004). Low resolution data (< 1 pulse/m², at ground level) is sufficient for the first method, whereas the second method requires high resolution data (approximately > 3 pulse/m²). The high resolution data has also been tested for change detection (e.g. Yu et al. 2004), growth measurements (e.g. Yu et al. 2005) and the determination of tree species (e.g. Holmgren and Persson 2004). However, to obtain forest attributes by tree species, aerial photographs are still needed simultaneously with ALS data (e.g. Packalén and Maltamo 2006). Typically, young forest stands have been problematic in remote sensing, but ALS data has also been tested successfully in these stands (Næsset and Bjerknes 2001). In fact, the results with ALS data have been so promising that the method based on low resolution data is used on a large scale in Norway (Næsset 2004).

1.2.2 Methods based on the follow-up of changes

Despite the error in forest inventory data gathered in the field by visual assessment, this method is also used by forest companies and by Metsähallitus. But, contrary to the periodic inventory conducted in private forests, they use continuous updating (Korhonen 2002, Koivuniemi and Korhonen 2006). In this method, the stand attributes are estimated in the field after an operation and stored in the databases. Stand boundaries are delineated with the help of new aerial photographs, with base maps or by GPS. Thus, stand attributes can be updated anytime computationally. With updated data, strategic and tactical planning and decisions can be based on the timely knowledge of forest resources. In addition, operative planning and subsequent activities become more cost-efficient (e.g. Kalland and Harstela 2003).

Despite the fact that the data model of Solmu/Luotsi system was designed to facilitate continuous updating for operational planning, this is not done in the RFCs. Thus, forest information is gathered by the expensive method but in RFCs it is often utilised only once in composing a forest management plan for the forest owner and thereafter to some extent in other regional tasks of RFC. One reason for the ineffective use of information is the organisational difficulties (Schneider 1999, Korhonen 2002). Namely, the forest data is gathered and managed by the RFCs but the forest operations are done by forest owners and by other actors and contractors. Until recent years, passing information about management operations between different actors has been difficult to arrange. Even the forest use declarations from forest owner to RFC have been delivered in paper form. Now these are mostly delivered in electronic form. Nowadays, it is possible to obtain information from the harvester about cutting tracks, stand boundaries and even the coordinates of the cut trees (e.g. Rasinmäki and Melkas 2005). In these circumstances, the lack of information and its passing between actors should not be an obstacle to updating databases according to completed management operations and thus, more effective use of forest information.

As most of the forest owners are members of the FMAs, FMAs are entitled to have forest management plans imported into their databases, generally in SilvaGIS. Therefore, FMAs utilise forest information in their own work, e.g. in marketing silvicultural operations, but only few update information in the FMA's data base. If an FMA carries-out or supervises the operation, it would be natural for the FMA to assess and update new forest attributes in the database and also to pass information forward. This could be done in association with normal work and with a minor amount of extra time (Hyvönen et al. 2005b).

In addition to updating, there have also been a few ideas to improve the accuracy and the productivity of the field work. The relascope has been an important measurement equipment, though the functionality has retained the same. Laasasenaho et al. (2002) (also Kalliovirta et al. 2005) developed a more versatile relascope, known as laser relascope or "relasnikov". In addition, a ground-based laser has been tested for the measurement of trees more accurately (e.g. Henning and Radtke 2006).

Some studies have concentrated on finding better measurement strategies in the field with respect to stand attributes, accuracy and time (e.g. Kangas and Maltamo 2002, Kangas et al. 2002, Mehtätalo and Kangas 2005) or improvement of the accuracy of the estimated diameter distribution (e.g. Haara et al. 1997, Kangas and Maltamo 2000a, Mehtätalo et al. 2006). These studies have shown that with different measurement strategies in different stands (optimising data collection at stand level) or the measurement of a few additional attributes, the accuracy of estimated attributes can be more reliable than in the present system. At the same time, the cost of the inventory can even be lowered.

MAF has stated that forest information should be extensive in relation to regions, recent enough and of good quality. (Maa- ja metsätalousministeriön… 2001). The purpose of forest inventory is to obtain information about forest resources at a specified time and at reasonable costs (e.g. Laar and Akça 1997.) Usually, the inventory system is decided on the bases of costs and quality. Either goal is to achieve the desired quality level and minimise the costs or with certain costs maximise the quality. In forest inventory, quality is often measured as accuracies (RMSE) of forest attributes. In Finland, no exact accuracy limits for data have been confirmed because the demand for accuracy can vary for different purposes. However, in evaluating new inventory methods, Uuttera et al. (2002) set a limit (RMSE, %) in mean volume at the stand-level to 15–35%, depending on the structure of the stand. The limits for diameter, height and basal area were 10–25%, 10–25%, 15–33%, respectively. The limits were set according to several studies concerning the accuracies of stand-level inventories in Finland (e.g. Poso 1983, Suutarla 1985, Laasasenaho and Päivinen 1986, Pussinen 1992, Pigg 1994). Larsson (1994) studied the timing of final felling and possible net present value losses due to the errors in stand data. He concluded that error levels of 10–20% in stand-level data cause bearable losses in relation to the cost of acquiring data of that quality. Thus, the accuracy demand was clearly higher than in Uuttera et al. (2002), but it must be noted that the study of Larsson (1994) concerned only older stands.

Real cost-efficiency can only be studied whit the whole inventory system and when the purpose of use is known. For example, in remote sensing related systems the costs are mainly dependent upon image material, the size of the area to be inventoried and the size of the reference data and how it is gathered. In this thesis, potential inventory methods for use in an inventory system were studied. As the total costs of the methods could not be calculated, interest was focused on the accuracies of forest attributes.

1.3 Objectives of the thesis

The purpose of this thesis is to develop and analyse cost-efficient forest inventory methods for forest management planning in NIPF in Finland. Cost-efficiency in this context means methods that produce stand attributes accurate enough for forest management plans and the costs are evaluated to be lower than in the present inventory system. Some of the tested methods are of interest mainly in Finnish forestry and some might be of interest also in other countries in the boreal zone. In fact, studies I, II and IV were designed to give some contribution to the development work of the new planning system (e.g. Paananen and Uuttera 2003, Rakemaa 2003, Kangas et al. 2006). Each of the individual papers concentrated on one topic, but at the same time could have some combined elements with other studies. To be more precise, the objectives of the papers were:

I   to study possibilities for updating stand-level forest attributes and silvicultural proposals with the help of medium spatial resolution (MR) imagery and another recently inventoried area as reference data,

II   to test segments as inventory and estimation units,

III   to test the possibilities of two-phase sampling at the segment-level,

IV   to discover the usefulness of different data bases for finding information about silvicultural operations and the reliability of an updated forest management plan, and

V   to test change detection with near optimal, very high spatial resolution (VHR) images when detecting thinnings.

2   MATERIALS

2.1 Field data

The study areas were located in Central, Western and Eastern Finland in five municipalities (Figure 1). The Solmu inventory data from NIPF owners estates gathered by Regional Forestry Centres (RFC) were used in studies I, IV and V. Meanwhile, the plot data used in studies II and III were gathered by FFRI based virtually on the Solmu system.

More exactly, two separate inventory data from two different inventory times were used in study I. The inventory data from Viippero, near Suonenjoki in North Savo, were collected in 1987 and 1999 and were used as reference data in the estimation. The inventory data from Mustinmäki, near Leppävirta, were from 1990/1991 and 2001 and were used as test data in the estimation. The distance between Viippero and Mustinmäki was approximately 50 km. Most of the stands in both areas were situated on mineral soils. There was more growing stock in the stands of Mustinmäki and the stands were spruce dominated compared to that in Viippero. Fieldcheck data were available from both of the areas. In Viippero 37, stands and, in Mustinmäki, 22 stands were fieldchecked by systematically placing, on average, 8 relascope sample plots in each stand.

The study areas of II and III were situated near Koli National Park in the municipality of Kontiolahti in North Karelia. The forest data was gathered between 2002 and 2003 from 10 different areas, their size varying between 7.5 and 53.6 ha and the total inventoried area was 163.8 ha. Most of the segments were on mineral soils. The mean area of the segments was 0.35 ha. The segments' attributes were assessed with the help of three to seven

relascope sample plots per segment. The stand characteristics for the sample plots and for the segments were calculated with the MELA2002 stand simulator (Redsven et al. 2002). The stand characteristics varied greatly between sub-areas. E.g. the mean volume varied between 80 and 202 m^3/ha and the mean height between 9 and 18 m.

Study area IV was situated near Mikkeli in South Savo. The forest data consisted of 20 NIPF owners estates that totalled 695 ha. The previous field inventory was conducted by the RFC in 1996 according to the Solmu system. Most of the forest area was spruce dominated (56%) and almost 90% of the area was either on fresh or dryish sites. All 20 forest holdings were used in analysing the possibilities to find information on operations from databases and 12 were used in examinations of stand simulations and the generation of forest management plans. These 12 forest holdings stands, altogether 526 ha, were field inventoried in 2002. In order to determine the accuracy of the inventory (2002) and the
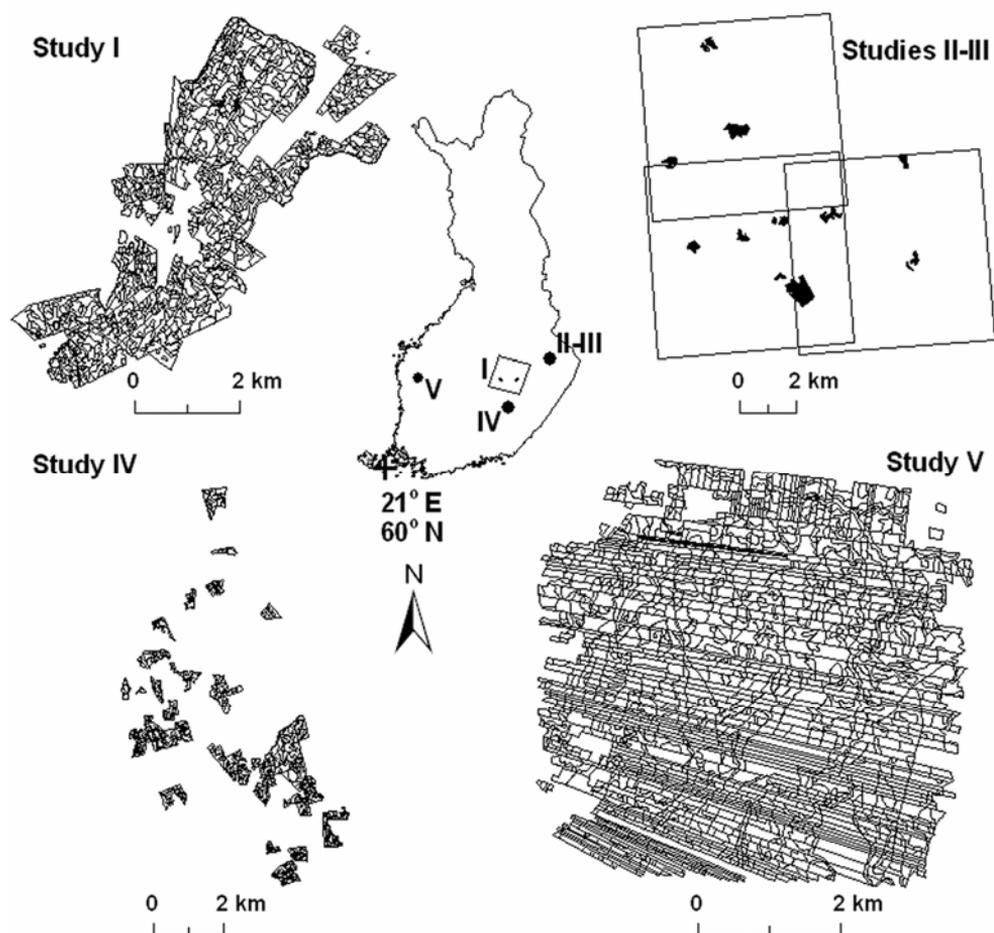
Figure 1. Study areas. The stand of Mustinmäki (upper left), the borders of aerial photographs of studies II and III and the boundaries of segments (upper right), the stands of study IV (bottom left) and the stands of study V (bottom right). The borders of the Landsat TM image used in study I are in the picture of Finland.

functionality of the growth models, 25 unchanged stands were measured with the help of 6 to 10 relascope sample plots that were systematically placed in the stands. On each relascope sample plot all trees were measured as tally trees and the basal area median diameter tree (DGM-tree) for each tree species and stratum was selected as a sample tree. The height was measured for all sample trees, as was age and the growth in diameter and in height for the past five year period on uneven sample plots.

Study area V was situated near the town of Kauhajoki in Southern Ostrobothnia. The inventory data was gathered by RFC in 2002 based on the Solmu system. Most of the forest area was pine dominated and 78% of the area was either on fresh or dryish sites. The shape of the stands (and holdings) is exceptional because the forest holdings are formed in strip shares, therefore the stands are usually long, narrow rectangles. The information on operations and changes in stands between 2001 and 2004 was collected from different databases of the RFC and some of the stands were checked in the field. According to this change information, every stand was classified into three classes for change detection analysis.

2.2 Remote sensing data

The imagery used in study I was Landsat 7 TM at a spatial resolution of 30 m. The imagery was taken on 2nd august, 1999 (bath 187, row 16, left lower quarter). The imagery was geo-referenced with the help of 43 ground control points to the spatial resolution of 25 m. The total RMSE of the rectification was 0.53 pixels. Channels 1–5 and 7 were used in estimations. Furthermore, age, mean volume and the proportion of the broadleaved trees of the old inventory data were added as additional channels.

Digitised colour-infrared aerial photographs for studies II and III were acquired on 29th July, 2001. The nominal scale of the images was 1:30 000. They were ortho-rectified to the Finnish coordinate system and resampled to a spatial resolution of 0.5 m. The rectification error varied between 3.3 and 4.8 m. In study II, one image was used and in study III, an image mosaic was composed from three images. The Landsat ETM, used in radiometric correction in study III, was taken on 20th June 2000 (bath 186, row 16). The imagery was geo-referenced on the basis of the ortho-rectified aerial photographs to the spatial resolution of 25 m. The total RMSE of the rectification was 0.25 pixels.

In study V, digitised colour-infrared aerial photograph pair from different years was used. The earlier image was acquired on 23rd June, 2001 and the latter one on 27th June, 2004. These images were taken almost with the same image specifications with respect to the sun's geometry, time and location. The nominal scale of the images was 1:30 000 and they were ortho-rectified to the Finnish coordinate system and resampled to a spatial resolution of 0.5 m. The total RMSE of the rectification was 5.1 m for the earlier imagery and 3.2 m for the more resent image.

3 METHODS

3.1 *K*-nearest neighbour (*k*-NN) estimation at stand-level (I)

The nonparametric *k*-nearest neighbour (*k*-NN) estimation method for stand attributes and for treatment proposals at the stand-level and at the segment-level was tested in study I. The Landsat TM 7 satellite's imagery channels 1–5 and 7 were used in the estimation. The old stand boundaries were used in the feature extraction in three different ways. In the first case, features were extracted from the whole stand as spectral averages. In the second case, features were extracted from the whole stand but the DN's were weighted in relation to the pixels' distance from the stand boundary. In the third case, features were extracted only from those pixels (core pixels) that were not connected to the stand boundaries. These stands are referred to as corestands. In this method, 377 stands were removed from the original 935 stands, because they had no core area.

In addition age, the mean volume and the proportion of the broadleaved trees of the old inventory data and the nearness of the coming cutting derived from the old inventory data were added as additional channels. The applied features in estimations were spectral averages of all the above-mentioned channels. The estimates for the stand attributes were determined as weighted averages of these spectrally nearest neighbours. The similarity was determined by using their Euclidean distance (Eq. 1) in the feature space.

$$d(x, y) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \tag{1}$$

where $d(x, y)$ is the Euclidean distance between feature vectors *x* and *y*.

When stand attributes were estimated, the nearest neighbours were weighted by the inverse squared Euclidean distance (Eq. 2) to decrease the bias in the stand estimates (Altman 1992).

$$\hat{y} = \sum_{i=1}^{k}\frac{1}{d_i^2} y_i / \sum_{i=1}^{k}\frac{1}{d_i^2} \tag{2}$$

where $\hat{y}$ is the estimate, *k* is the number of neighbours y_i is the value of *y* of the *i*'th nearest neighbour and d_i is the Euclidean distance to the *i*'th nearest neighbour. There is a small possibility that the Euclidean distance is zero leading up to division by zero. This was avoided by adding a small constant to Euclidean distance in equation two.

The treatment proposals were estimated with an un-weighted *k*-NN. The proposal, or in some cases proposals, with the largest frequency was chosen for further examination. After checking the proposal's logic with respect to the old inventory data, it was accepted as the estimate. The estimates were compared to the proposals given subjectively in the field.

According to the fieldcheck data, the stand attributes of Viippero were found to be quite inaccurate and biased. For example, the mean volume was underestimated by 13.8% and the mean diameter by 19.9% (I, table 2). Therefore, in the estimations, the calibrated reference data of Viippero were also used in order to obtain a more realistic idea of the estimation method.

The aim of the estimation test was to produce stand attributes for the new planning area. In this case, stand boundaries were available but in practice they are usually not. Thus, segments were also used as feature extraction units and in estimations. The segmentation procedure is described in more detail in study II and in the next chapter. Although segments were used as estimation units, the reliability of the estimations was studied at the stand level. This means that the estimates for the stand were calculated as an average from those segments that the stand clipped.

The reliability of the stand attributes estimates were examined by means of root mean square error (RMSE), relative RMSE, bias and relative bias. The accuracy of the treatment proposals were evaluated by means of confusion matrices and by κ (Kappa) coefficient (Rosenfeld and Fitzpatrick-Lins 1986).

3.2 *K*-NN estimation at segment-level and two-phase sampling (II–III)

In studies II and III, segments as an inventory and as an estimation unit were tested. In study II, estimation was done both at the sample plot and at the segment-level and in study III at the segment-level.

In both studies, the segmentation was conducted, in general, with the same procedure. First the images were resampled to a spatial resolution of 1 m. Next they were smoothed with a Gaussian filter.

After smoothing, the images were segmented with the two phase segmentation algorithm developed in FFRI. In the first phase, the algorithm produced initial segments, which are very small in area and homogeneous with respect to the applied features. In both studies, the spectral features of all three channels were applied. In the second phase, these small initial segments were fine-tuned with a region-merging algorithm. In this procedure, the smallest segments are merged to the spectrally nearest neighbouring segments. Larger segments, if they are similar enough, are also merged together. The similarity between the segments was determined using their Euclidean distance in the feature space:

$$d(s_i, s_j) = \sqrt{\sum_{ch=1}^{n} (\bar{x}_{i,ch} - \bar{x}_{j,ch})^2} \qquad (3)$$

where $d(s_i, s_j)$ is the Euclidean distance between segments *i* and *j*, $\bar{x}_{i,ch}$ is the mean intensity of the channel *ch* of the segment *i* and *n* is the number of channels.

The *k*-NN estimation procedure was similar to study I. The image features applied in estimations were spectral averages and standard deviations of all three channels. In sample plot estimation, the features were extracted from a window size of 21 x 21 m and in the segment-level estimations from the whole segment.

As the aerial photographs are strongly affected by the bidirectional reflectance effect, the image mosaic of study III was radiometrically corrected by the method developed by Tuominen and Pekkarinen (2004). The idea of this method is to locally adjust the aerial photographs' intensities to the local intensities of the reference image, which is less affected by the bidirectional reflectance effect. In this study, the Landsat 7 ETM was utilised as a reference image. The correction was carried-out as a local adjustment of the image mosaic spectral values. The correction unit was a segment. The correction was done

for all channels separately, with the use of Landsat ETM channel 2 for green, ETM3 for red and ETM4 for NIR channel. The correction method is straightforward, it does not need any priori information and the preliminary results have been promising. Thus, this method was chosen for radiometric correction. The estimation tests were done for original and radiometrically corrected image mosaics alike.

The study materials in both studies were quite limited, therefore the estimation tests were conducted with the cross-validation technique. In study II, the segment level cross-validation tests were carried-out separately for both of the study areas and for their combination. The sample plot level tests were carried-out using two different methods. In the first method, the nearest neighbours were found among all the field sample plots, except the one for which the estimation was done. In the second method, only one randomly selected field sample plot from each segment was used. In study III, the estimations were conducted at segment-level and no restriction for the location of the nearest neighbour was applied.

Study II revealed that the field work of small segments is considerably slower than normal stand-level forest assessment. One possibility for rationalisation of the segment-level inventory would be the application of sampling with stratification (double sampling or two-phase sampling, e.g. Poso 1972, Poso and Kujala 1971, Cochran 1977) which was tested in study III. The segments were stratified into several strata by k-means algorithm (McQueen 1967) based on the segments' spectral features. After stratification, the sampling units (segments) were allocated to the strata by two different methods: by proportional allocation and by optimal allocation (also known as Neyman allocation) (e.g. Cochran 1977, Kangas 2006). In both methods, the number of sample segments was set to 100. In proportional allocation the number of sample segments was proportional to the size of the stratum. In optimal allocation the number of sample segments was dependent both on the variation within the stratum and the size of the stratum. The sampling was done by simulation.

In both studies, the reliability of the estimates were evaluated by means of RMSE, relative RMSE, bias and relative bias. In study III, the reliability of the sampling was studied by calculating the standard error of the mean volume within the stratum (eq. 4) and the area weighted standard error of the whole area (eq. 5).

$$s.e._h = \sqrt{\frac{\sum_{i=1}^{s} (\bar{y} - \hat{y})^2}{s-1}} \tag{4}$$

$$s.e. = \sum_{h=1}^{L} \frac{Ah}{A} * s.e._h \tag{5}$$

where $s.e._h$ is the standard error of the mean volume in stratum h, $s.e.$ is the area weighted standard error of the mean volume, s is the number of simulations in the stratum, $\bar{y}$ is the mean volume in the stratum, $\hat{y}$ is the mean volume of the simulation, A_h is the area of stratum h, A is the area of the strata and L is the total number of individual stratum.

3.3 Follow-up of changes

3.3.1   Collecting information on operations and computational updating (IV)

In study IV, the possibility for gathering information on operations (i.e. cuttings and silvicultural treatments) from RFC's and FMA's data-bases was explored. Based on this information, two differently composed forest management plans were compared. In the first case, the traditional forest management plan (FMP) was composed based only on new inventory data. In the second case, an FMP was composed by updating computationally old inventory data (from 1996). In this method, stands with no operations were updated by growth models. Meanwhile, stands that were operated according to information found from data-bases were updated by new data inventoried in the field.
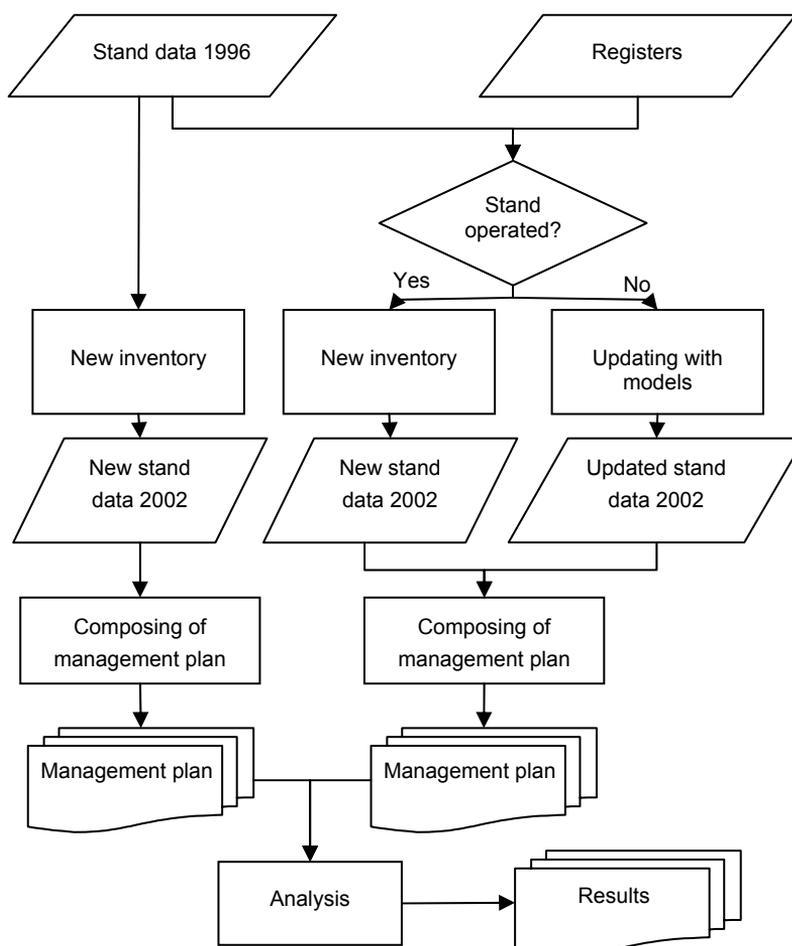
Figure 2. Flow chart of the composition and comparison of forest management plans.

The stand simulator MELA2002 was used to produce stand attributes and future treatment proposals in both cases. The cutting and silvicultural proposals and their timings, proposals area, cuttings removal, incomes and costs for the FMP's were studied. The procedure of how two different FMP's were composed and compared is shown in Figure 2.

The mean volume of the stand in the check data was estimated in four steps:
1. Height for sample trees was estimated with the height models of Veltheim (1987).
2. Height for tally trees was estimated with the height models of Veltheim (1987) and calibrated with the help of measured sample tree heights.
3. Volume for tally trees was estimated with the volume functions of Laasasenaho (1982) with measured dbh and estimated height as independent variables.
4. Volumes by trees were converted to volumes by hectares and added-up by tree storeys.

The growth in volume for sample trees was estimated with the method illustrated by Kujala (1980). The growth in volume was assessed in order to discover the possible clear errors in old inventory data and in growth models. The growth was converted to an increment percent. Furthermore, the growth in volume in the stand was calculated by multiplying the volume of trees with the increment percent by tree species. This volume was then compared to the volume of stand inventory that was made in 2002.

3.3.2 Change detection (V)

In study V, change detection using bi-temporal aerial photographs was tested. The stands in the reference and in the test data were classified into three classes according to the type of change: No-change class, Moderate-change class and Considerable-change class. Most interest was focused on the Moderate-change class and especially in finding thinnings.

Aerial photographs are strongly affected by the bidirectional reflectance effect and the sun-object-geometry, which causes radiometric distortions on the images (e.g. Campbell 1987, Singh 1989, Holopainen & Lukkarinen 1994). Because of this, similar forest stands may have different spectral characteristics in different parts of the image. In order to reduce this effect, images were radiometrically corrected by two methods: by rationing and by an empirical correction chain. The radiometric correction was done to the images that were resampled to a spatial resolution of 3 m. In rationing, three new images per date were calculated by the following ratios: IR/R, IR/G and R/G. One new image per date was calculated with the empirical correction chain. In this procedure the aim is to reduce both the light falloff effect and bidirectional reflectance effect with the information of sun angles, flying altitude and vegetation type. A detailed description of this method is in study V and Pellikka 1996 and 1998.

Several spectral, histogram and textural features were extracted for stands leading in the 11 different data sets. The features were extracted from the original and radiometric corrected images alike. It was also tested for whether the results of change detection could be improved with stand attributes from the old inventory. This was done only with the data set that performed best in change detection.

The change detection was accomplished with stepwise discriminant analysis (Tabachnick and Fidell 1989, SPSS 2005). The classification functions were estimated in the reference data for three change classes and these functions were tested in the test data. The accuracy of the classification results was evaluated by means of confusion matrices

(Campbell 1987). Thus, overall, the user's and producer's accuracies (Stehman and Czaplewski 1998) as well as the κ coefficient were used. In addition, the factors that affect the change detection were tested by logistic regression.

4 SUMMARY OF THE ARTICLES

4.1 *K*-NN estimation at stand-level (I)

The correlations between the whole reference data and the Landsat TM image channels were all negative and varied between -0.120–-0.697. The best correlations between stand attributes and image channels were found with the spectral averages of channels 4 and 5. The best correlation was between channel 5 and basal area (-0.697). The highest correlation in the group of corestands was between the spectral average of channel 5 and basal area (-0.795).

The highest accuracies in the cross-validation of mean volume with reference data was achieved by using spectral averages of Landsat TM channels 1–5 and 7 of corestands and three additional channels of old inventory data: age, mean volume and the proportion of the broadleaved trees. The highest accuracies in the cross-validation of treatment proposals with reference data was achieved by using spectral averages of Landsat TM channels 1–5 and 7 of corestands and all four additional channels of old inventory data. Thus, the final estimations were done with these features. A group of 377 stands did not have core area, therefore spectral averages or weighted averages were utilised in estimations for these stands.

In the stand-level estimation, when attributes for 921 stands in Mustinmäki were estimated using 935 of those in Viippero, the relative RMSEs varied between 34.1–168.2% and was lowest with mean height. The relative bias varied from an underestimation of 23.1% of the mean volume of deciduous trees to an overestimation of 25.3% of the mean volume of pine. The accuracy of estimation was significantly higher when calibrated reference data was used. The relative RMSEs dropped 3.7–5.4 %-units and the biases were also mainly smaller. When only development classes from young-aged to mature stands (development classes 02-04) were studied, the relative RMSEs were 10.7–21.2 %-units lower compared to the results of all development classes (I, tables 4 and 5). Furthermore, estimation accuracy improved when small stands were left out. The relative RMSE of all stand estimates decreased by approximately 13 %-units when the minimum stand area was 2 ha.

At the segment-level, the results were slightly worse than at stand-level. The relative RMSE of mean volume was 62.5% and the bias -7.3%. The RMSE with other stand attributes varied between 46.2–166.5% and the bias -25.5–13.0%. As with the stand-level, the relative RMSEs were 12.5–23.3 %-units lover in development classes from young-aged to mature stands than in the total data.

The estimated treatment proposals did not fit those given in the field. The overall accuracy of the cutting proposals was 57.6% and that of silvicultural proposals 71.2%. The κ values were 0.35 and 0.36, respectively.

According to fieldcheck data (Viippero 37 stands and Mustinmäki 22 stands), data in Mustinmäki and Viippero had errors in the stand attributes. In particular, the attributes in Viippero were clear underestimates, varying between 0.9–49.5% (I). Therefore, the

estimation accuracy was studied more closely in these checked stands. The attributes for Viippero was estimated with Viippero reference data (without checked stands) and for Mustinmäki with calibrated reference data from Viippero. In both areas, the relative RMSEs of the estimates were clearly smaller than in total data estimations, varying between 11.8–122.7%.

4.2 *K*-NN estimation at segment-level and two-phase sampling (II–III)

At the estimation of the segment- and plot-level attributes, the *k*-values 1–15 were tested and it was noticed that the *k*-value 5 worked best. The absolute values of correlation coefficients between the segments' attributes and average intensities of the image channels varied between 0.02–0.82 (II). All segment attributes, other than mean volumes of pine and deciduous trees, had correlations with average intensities of the image channels over 0.53.

At the sample plot-level estimation (II), the relative RMSEs varied between 31.8–134.2%. When the number of sample plots was reduced to one from each segment, the relative RMSEs increased by 4–11.5 percentage units. The lowest RMSE, 31.8%, was found for the estimate of the mean height.

At the segment-level estimations, the relative RMSEs varied between 34.7–118.4% (II) and 36.8–137.0% (III). Study II included two separate areas and study III included the same two areas and 8 additional areas. The lowest RMSEs in both studies were found for the estimates of mean height, 34.7% (II) and 36.8% (III).

The radiometric correction did not significantly affect the estimation results. In contrast, as expected, the relative RMSEs were 1.0–20.1 percentage units higher in the estimation with radiometrically corrected than uncorrected features. Meanwhile, the relative biases were 0.3–4.3 percentage units lower.

The reliability of estimation of mean volume was also studied with confusion matrices in volume classes of 50 and 100 m^3/ha. The overall accuracy of mean volume with volume classes of 50 m^3/ha was 37.5% (uncorrected image mosaic) and with volume classes of 100 m^3/ha 52.5% (radiometrically corrected). The Kappa values were 0.26 and 0.35, respectively.

In study III, in addition to estimations, stratification and sampling were carried-out in order to test the usability of the segments in an operational inventory. As the number of strata increased from 40 to 60, the standard deviation of the mean volume decreased from 68.4 m^3/ha to 63.4 m^3/ha. On the contrary, the RMSE of the mean volume increased as the number of strata increased. The RMSE of the mean volume varied between 35.3–41.7 m^3/ha as the number of strata was 40 and between 38.0–48.5 m^3/ha as the number of strata was 60 (III, table 3). The proportional allocation in sampling produced mainly smaller RMSEs than the optimum allocation.

4.3 Follow-up of changes (IV–V)

Over the six year period, 39.3% of the stands were operated according to field inventory (IV). Only 48.1% of these operations were found from the data bases of RFC and 70.0% of FMA. As forest owners were interviewed, altogether 92.8% of the operations were found. Despite the fact that the forest owner must do the forest use declaration to the RFC

according to the Forest Act (Forest Act 1093/1996), surprisingly, only 60% of the regeneration cuttings were found from the data bases of the RFC.

In the simulations of the cutting proposals for all stands (470 stands) for the first five year period, there were only slight differences between the proposals generated from updated data (i.e. operated stands attributes from new inventory data and others from old inventory data by growth models) or from new inventory data. In the updated data, the stand simulator MELA generated cutting proposals for 15 stands that were left to rest in the new inventory data (Table 4, IV). Secondly, cutting proposals were generated for 16 stands in the new inventory data that were left to rest in the updated data. The overall accuracy when proposals were classified into three classes was 91.3% and the Kappa value was 0.86. When the comparable proposals were generated only for unchanged stands (288 stands), the overall accuracy was 85.8% and the Kappa value was 0.78. The proposals for the tending of seedling stands were generated for 22 stands with the new inventory data which were left to rest in the simulations with updated data. The overall accuracy was 94.9% and the Kappa value was 0.8.

Both simulations clearly generated more cutting proposals than were given in the field by the inventory. Meanwhile, proposals for the tending of seedling stands were proposed more in the field than they were generated in the simulations.

In the simulations, the mean volume of the updated stands was 135.1 m^3/ha and 125.0 m^3/ha of the new inventory data, so the difference was 10.1 m^3/ha (8.1%). When only unchanged stands were compared, the difference was 16.5 m^3/ha (10.5%). In addition, the cutting removal in the first five year period was 8% higher with the updated data than with the new inventory data.

According to the check data (unchanged 25 stands), the RMSE of the mean volume was 17.0% with the new inventory data and even lover, 14.4%, with the updated data. The relative bias was 2.9% and -1.7%, respectively. However, the RMSEs and the biases of the volumes of tree species were clearly higher in both sets of data. The estimated increment in volume in the check data (based on sample trees) was 49.3 m^3/ha. The increment estimated with the stand simulator MELA was an average 4.4% bigger. The RMSE between these two was 24.6%.

As study IV revealed, all changes in the forest cannot be found from data bases. Under these circumstances, the change detection from bi-temporal aerial photographs was tested for in study V. The overall accuracy of classification varied between 75.3% and 84.7% and Kappa value varied between 0.40 and 0.58, respectively. The best accuracy in classifications was achieved with the use of a histogram and textural features together with the standwise spectral medians of the digital numbers (*OrigHisTex*). Noticeably, only 17 features of a total of 93 possible *OrigHisTex* features were selected in the classification procedure. With this data set the omission error was 19.3% and commission error 14.5%. Though the omission error was rather high, considerable changes were found without error and also 84.2% of the thinnings.

The resolution of the aerial photographs did not significantly affect the accuracy of classification. The original image resolution of 0.5 m performed equally well to those of 3 m. In addition, neither of the two radiometric correction methods, rationing and empirical, improved the classification accuracy. This was most likely due to the fact that the photographs were shot with almost identical image specifications.

As the considerable changes were classified reliably, the effects of stand properties in classification were analyzed in the No-change and Moderate-change classes. In the No-change class, stands with a high volume of birch were more often classified as unchanged

than the stands with a low volume of birch. Meanwhile, tall stands far from the nadir and also front-lighted stands far from the nadir were often misclassified as changed. In the Moderate-change class, very sparse and well-stocked stands were often misclassified as well as dense stands near the nadir.

5 DISCUSSION

5.1 Discussion of the main results

As studies I-III revealed, the estimation based on remote sensing material was not reliable enough to produce forest inventory data for forest management planning in private forests. Although the accuracies at stand-level were near the accuracy limits of Uuttera et al. (2002), all the mean values of the tree species or tree cohorts could not be estimated. These stand characteristics are essential, as they are used as an input in forest management planning systems. In study I, estimated silvicultural proposals and their areas were compared to those given by a surveyor. The classification accuracy was only 58% (Kappa value 0.35) but the areas by treatment classes were near the same as in management plans. It was also noticed that the classification accuracy for proposals of first thinnings were 68% and only 19% of the stands to be thinned were not found. The image material of study I is relatively cheap and the estimation procedure straightforward. Thus, this method could be used for large areas when estimating approximate forest attributes and sum characteristics and to some extent as information for less active forest owners or for forest owners who accept less accurate information.

Segment-level inventory and estimation proved to be a promising alternative method for gathering forest information. It was, perhaps, the first time that this kind of segment-level inventory, made in studies II and III, was tested in respect to fieldwork and k-NN estimation. The variation in forest attributes and in the spectral features of aerial photographs between study areas were quite high. In association with a low number of segments, the estimation results were more inferior than expected. The writer's opinion is that in the k-NN method the size of the reference data should be several hundreds; the more variation there is in the data, the more reference data is needed. If the variation is small, the size of reference data is not so critical. Especially in study III, the two-phase sampling would have needed larger data for proper testing and a more reliable evaluation of the method. In study III the image local radiometric correction did not improve the results. One possible reason for this is the one year differences in acquisition time between the aerial photographs and the Landsat ETM. Forest operations might have taken place between acquired images which have effects on the correction method. Those segments spatial near forest operations, in particular, might have got incorrect intensities in radiometric correction due to the large pixel size of the Landsat image. The optimal situation, for radiometric corrections, is to obtain images at the same time, but this is difficult to arrange.

In studies I-III, only spectral features were used in the estimations. In studies II-III textural features were left out because of the complicated form and small size of the segments and in study I because of the small size of the stands and large pixel size of the Landsat TM image. Nilson and Peterson (1994) discovered that after the canopy closes, the reflectance remains approximately the same regardless of further growth. This leads to weak correlations between forest characteristics and spectral features in mature stands.

Furthermore, Haralick et al. (1973) stated that the texture measures derived from the spatial grey-tone co-occurrence matrix gives reasonable results, especially with satellite images. Thus, textural features should have been tested at least in study I.

In the case of VHR images, the segmentation algorithm and image processing plays an essential role in the processing of the data. In the segmentation, the first phase initial segments are truly homogeneous, provided, of course, that the right parameters have been used. In the second phase, where initial segments are merged to form segments feasible for field inventory, the homogeneity might decrease. With accurate GPS-equipment, it would be possible to measure sample plots from the initial segments and to use these initial segments as estimation units. This is close to the approach used by Pekkarinen and Tuominen (2003). The homogeneity of the segments could be enhanced with additional information in addition to spectral information. One interesting experiment would be, e.g., the use of height information of the ALS data.

Another problem related to the segmentation with VHR images is the shadow-effect. Shadows usually form their own segments at the edge of mature stands, open areas or even inside sparse stands, according to the position of the sun. The spectral features from these segments are similar to those of mature stands but the forest attributes might be totally different, which confuses the estimation. This complication could be resolved using methods similar to those studied by e.g. Liira et al. (2006).

Study IV demonstrated the usability of different registers for finding management operations. As most of this information was only on paper form, the utilisation was laborious. In some cases, the information was labelled on incorrect stands because of mistakes in stand numbers. Still, 75% of the management operations done in a five year period were found from registers. In the future, utilisation of these registers will be much easier and more reliable, as the information is saved and processed in electronic form and reliably linked to the stand in question. The reliability of the updated forest data was equal to the reliability of the new inventory data. In addition, the management proposals in the management plans were similar. Based on these findings, it was concluded that the use of growth models for relatively short periods is reliable. Ojansuu et al. (2002) and Haara and Korhonen (2004a), e.g., also found that the biggest source of error in updating are the erroneous forest attributes of the initial state.

Study V concentrated on change detection and its contribution to updating. As in many previous studies using VHR or MR images, clear changes were detected reliably. For moderate changes the results were somewhat better than in earlier studies. Although one fifth of the changed stands were not detected, 84.2% of thinned stands were classified correctly. The most difficult changes to detect were stands with slight storm damage and removal of hold over trees, as well as tending of seedling stands (V, Fig. 3). Nevertheless, the overall accuracies varied between 77.3–84.7%. These results would probably be better if stand information from different registers was to be co-ordinated with change detection. In this test, the whole image area was used. Because of the strong bidirectional reflectance effect in aerial photographs, better results might have been achieved if only a central part of the image had been used.

Many studies have concentrated on image radiometric corrections (e.g. Holopainen and Wang 1998, Tuominen and Pekkarinen 2004). Surprisingly, the radiometric correction of digitised images did not improve the classification accuracy in study V. It was concluded that the reason for this is that bi-temporal images were acquired with same image specifications with respect to location and time. Despite this result, radiometric corrections

should be considered and new straightforward methods tested with new, digital by origin, images.

5.2 Conclusions and future research needs

The remote sensing based estimations of forest attributes studied here did not meet the accuracy limits at stand-level set by Uuttera et al. (2002). However, the accuracy of the segment-based inventory method was close to the limits. Thus, this method could be used in the estimation of forest attributes and treatment proposals, e.g. for passive estates, which have not ordered a forest management plan. As it was considered to be a promising method, it should be developed further. The next step, in addition to improving the estimation accuracy, could be to study how the segments can be aggregated into reasonable treatment units (cf. Laiho 2004). Also, the use of segments instead of predefined compartments in spatial optimisation can offer more flexibility and can lead to more effective use of forest resources (cf. Holmgren & Thuresson 1997, Heinonen 2007).

The results of study IV and the preliminary results of Hyvönen et al. (2005b) have shown that the inventory of operated stands might also be cost-effective in private forests. In this method, the information regarding operations is gathered from different registers and from wood purchasers. The updates in the field can be done after operation or a few times a year, adapting to the best suitable time. If the stand is inventoried soon after operation, the quality of the work can be checked (Korhonen 2002). In addition, with accurate field inventory future updating with models will be more reliable (Ojansuu et al. 2002, Haara and Korhonen 2004a). Quite the contrary, Ståhl et al. (1994) discovered that an accurate inventory well ahead of the calculated optimal harvesting is most profitable. They also found that a series of cheap and moderately accurate inventories were better than one expensive and accurate inventory before harvesting. The findings of Holmström et al. (2003) were similar to Ståhl et al. (1994). They concluded that the best inventory method depended on the type of the stand. Large mature stands should be accurately inventoried close to the next treatment and less valuable stands with less accurate methods. So, there are the questions of which inventory method is better and should the stand be inventoried before or after operation. This leads to the conclusion that different methods should be applied side-by-side in different stands and in different planning purposes.

It is most likely that the information from all completed operations from different actors is not acquired. Therefore, there should be a method to control the extensiveness of gathered information. There is also a need to find unexpected changes, such as storm damage, and to control errors in databases. One possibility is change detection based to remote sensing material. In Finland, the size of private forest stands favours HR images instead of MR images. Thus, the aerial photographs acquired for forest inventory purposes can also be utilised here. Therefore, the change detection method tested in study V in combined use with the information of operations in data bases could offer some contribution to forest inventory. At least it can provide supplementary information for updating and for allocating the fieldwork. However, for reliable change detection, the time between images can not be several years (cf. Wilson and Sader 2002).

The possible inventory and updating of a forest resource data system, based partly on findings in this thesis, is outlined in Figure 3. The acquisition of forest attributes can be based, e.g., on accuracy demand, allowable costs or cost-plus-loss analysis. In addition, the

"end user", the forest owner, should be aware of different methods and the accuracy levels of forest attributes.

Fieldwork will still have a remarkable role in forest inventories. To obtain reliable estimates with remote sensing data, sufficient reference data is needed. The most likely way is to collect the data by field inventories and in some cases the stand data can be usable. On the other hand, some of the reference data could be gathered from the harvester, as mentioned earlier. If remote sensing data is acquired just before clear cutting of the stand, harvester data could then be used as reference data in interpretation. As e.g. Packalén (2006) has stated, new field data is needed for each new inventory region when ALS data is
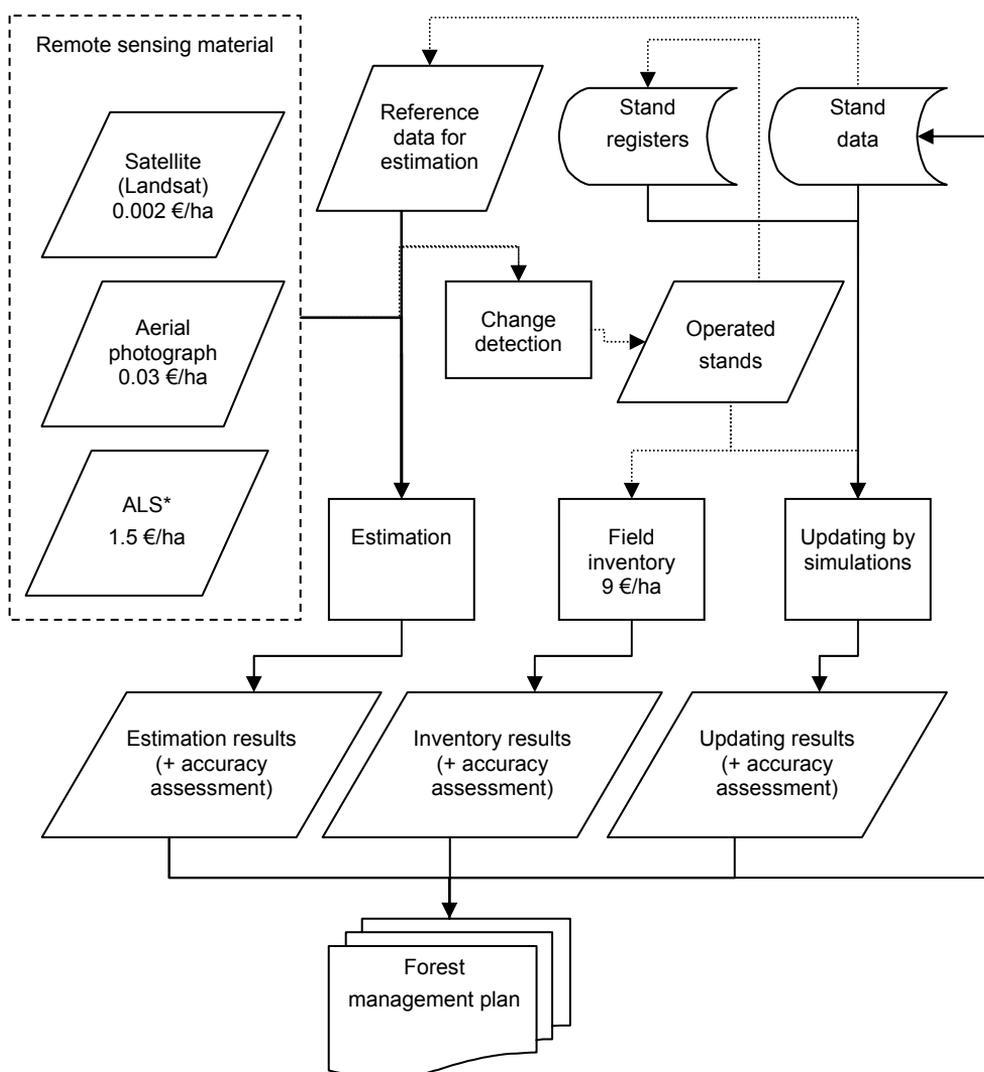
Figure 3. A simplified diagram of possible methods for updating forest attributes. The approximate prices of different remote sensing materials and field inventory are shown in graphs. (* < 1 pulse/m^2 at ground level).

applied. In addition some special stands, like seedling stands and stands with valuable diversity need to be checked and inventoried in the field. Another thing to decide is how to define future treatment proposals. If the stand estimates obtained with remote sensing data are accurate enough, proposals could be generated to some extent from the estimated data but most probably a fieldcheck is also needed. It must be kept in mind that the forest owner's opinion of the stand's treatment do not necessarily coincide with those generated from the data.

In these circumstances, some effort towards rationalising fieldwork should be done. Despite the continuous training of surveyors offered by the RFCs, the RMSEs of the forest attributes have been at the same level. New studied inventory strategies, which were discussed earlier in the introduction, should be tested with larger data and in different circumstances. New measuring devices should also be invented and tested. In the future, stand attributes might be estimated based on digital image acquired on the ground (e.g. Varjo et al. 2006) or from laser data acquired from a vehicle cruising in the forest (e.g. Jutila 2006). However, the most realistic alternative in the near future is that data is concurrently collected by a harvester whilst felling (e.g. Stendahl and Dahlin 2002). If the accuracy of updating is not so essential, some operations could be updated without fieldwork by simulations (cf. Hyvönen et al. 2005a). Nevertheless, exact information of the time of the operation and its quality will lead to more reliable results in simulations.

Despite encouraging experiences in follow-up changes and updating of forest attributes, there are still some related issues to resolve. First of all, what are the legal restrictions concerning the forest resource data and its delivery between the actors of private forestry; even if the information of operations is available to all actors. Secondly, if the information can be delivered, new techniques and mechanisms are needed for flexible transferral of the data.

The ALS data combined with digital aerial photographs have been widely studied in recent years. There is strong belief that they are used in a new inventory system in Finland to produce accurate forest characteristics at stand- or at segment-levels (e.g. Packalén 2006, Uuttera et al. 2006). The planning system can be utilised more effectively with updated forest resource data. There is no knowledge of how recent the data should be. If the forest resource data in the new inventory system is produced with the help of ALS and HR image materials, the inventory cycle can even be one year. This is dependent on the resources and, in the future, mostly on the costs of ALS and image materials. Thus, 3–10 years is realistic interval. In this period, a great proportion of stands information have changed and the information in data-bases are no longer recent enough. If the attributes of the stand are not updated after operation, at least information regarding changes in stands should be stored in databases annually. This will make the information in databases more reliable and also rationalise the use of information in operational activity.

Though a lot of interest is focused on reducing the costs of inventory and increasing the accuracies of the forest attributes, cost-efficiency when forest inventory and decision making are looked at concurrently should also be studied more closely. For this kind of approach, cost-plus-loss analyses have been suggested (e.g. Cochran 1977, Ståhl et al. 1994, Eid 2000, Holmström et al. 2003, Eid et al. 2004, Juntunen 2006). In these approaches, the total costs are minimised. The total costs include the cost of inventory and the expected losses of wrong decisions based on uncertain forest data. Thus, whenever the additional costs of inventory are less than the additional income, the method is suitable for the forest owner. This "decision oriented inventory planning" concept should arouse some discussion and research ideas.

REFERENCES

Altman, N. 1992. An introduction to kernel and nearest-neighbor nonparametric regression. The American Statistician 46(3): 175−185.

Anttila, P. 2002a. Updating stand level inventory data applying growth models and visual interpretation of aerial photographs. Silva Fennica 36(2): 549–560.

– 2002b. Nonparametric estimation of stand volume using spectral and spatial features of aerial photographs and old inventory data. Canadian Journal of Forest Research 32: 1849–1857.

– 2003. VISU-tuotantotestaus. Loppuraportti. Forestry Development Centre Tapio. Helsinki, Finland. 13 p. (In Finnish).

– 2005. Assessment of manual and automated methods for updating stand-level forest inventories based on aerial photography. Dissertationes Forestales 9. Doctoral Thesis, University of Joensuu, Faculty of Forestry. 42 p.

– & Lehikoinen, M. 2002. Kuvioittaisten puustotunnusten estimointi ilmakuvilta puoliautomaattisella latvusten segmentoinnilla.

Atkeson, C.G., Moore, A.W. & Schaal, S. 1997. Locally Weighted Learning. AI Review 11: 11−73.

Bitterlich, W. 1948. Die Winkelzählprobe. Allgemeine Forst- und Holzwirtschaftliche. Zeitung, 59 ½: 4–5. (In German).

– 1984. The relascope idea. Commonwealth Agricultural Bureaux. Farnham Royal. 242 p.

Bolduc, P., Lowell, K. & Edwards, G. 1999. Automated estimation of localized forest volume from large-scale aerial photographs and ancillary cartographic information in a boreal forest. International Journal of Remote Sensing 20(18): 3611–3624.

Campbell, J.B. 1987. Introduction to remote sensing. The Guilford Press, New York. 551 p.

Cochran, W.G. 1977. Sampling techniques. 3rd edition. John Wiley & Sons, New York. 428 p.

Cohen, W.B. & Spies, T.A. 1992. Estimating structural attributes of Douglas-fir/western hemlock forest stands from landsat and SPOT imagery. Remote Sensing of Environment 41(1): 1–17.

Davis, L.S. & Johnson, K.N. 1987. Forest management. 3rd edition. McGraw-Hill Series in Forest Resources. USA 790 p.

Eid, T. 1990. Long term forest planning. Economical and biological possibilities of a forest. Agricultural University of Norway, Department of Forestry. Doctor Scientiarum Theses 1990:9. 143 p. + appendixes.

– 2000. Use of uncertain inventory data in forestry scenario models and consequential incorrect harvest decisions. Silva Fennica 34(2): 89–100.

– & Næsset, E. 1998. Determination of stand volume in practical forest inventories based on field measurements and photo-interpretation: the Norwegian experience. Scandinavian Journal of Forest Research 13: 246–254.

– , Gobakken, T. & Næsset, E. 2004. Comparing stand inventories for large scale areas based on photo-interpretation and laser scanning by means of cost-plus-loss analyses. Scandinavian Journal of Forest Research 19: 512–523.

Finnish Statistical Yearbook of Forestry. 2006. Finnish Forest Research Institute. 438 p.

Foody, G. 2002. Status of land cover classification accuracy assessment. Remote Sensing of Environment 80(1): 185–201.

Forest Act 1093/1996.

Fournier, R.A., Edwards, G. & Eldridge, N.R. 1995. A catalogue of potential spatial descriminators for high spatial resolution digital images of individual crowns. Canadian Journal of Remote Sensing 21: 285–298.

Franco-Lopez, H., Ek, A. & Bauer, M. 2001. Estimation and mapping of forest stand density, volume, and cover type using the k-nearest neighbors method. Remote Sensing of Environment 77(3): 251−274.

Franklin, S., Hall, R., Moskal, M., Maudie, A. & Lavigne, M. 2000. Incorporating texture into classification of forest species composition from airborne multispectral images. International Journal of Remote Sensing 21(1): 61−79.

Gougeon, F. 1995. A crown-following approach to the automatic delineation of individual tree crowns in high spatial resolution aerial images. Canadian Journal of Remote Sensing 21(3): 274–284.

Goward, S.N., Davis, P.E., Fleming, D., Miller, L. & Townshend, J.R. 2003. Empirical comparison of Landsat 7 and IKONOS multispectral measurements for selected Earth Observation System (EOS) validation sites. Remote Sensing of Environment 88(1): 80–99.

Haapanen, R. & Pekkarinen, A. 2000. Utilising satellite imagery and digital detection of clear cuttings for timber supply management. In: International Archives of Photogrammetry and Remote Sensing, Vol. XXXIII, Part B7: 481–488.

Haara, A. & Haarala, M. 2002. Tree species classification using semi-automatic delineation of trees on aerial images. Scandinavian Journal of Forest Research 17: 556–565.

− & Korhonen, K.T. 2004a. Toimenpide-ehdotusten simulointi laskennallisesti ajantasaistetusta kuvioaineistosta. Metsätieteen Aikakauskirja 2/2004: 157–173. (In Finnish).

− & Korhonen, K.T. 2004b. Kuvioittaisen arvioinnin luotettavuus. Metsätieteen Aikakauskirja 4/2004: 489–508. (In Finnish).

− , Maltamo, M. & Tokola, T. 1997. The k-nearest-neighbour method for estimating basal-area diameter distribution. Scandinavian Journal of Forest Research 12: 200–208.

Häme, T. 1991. Spectral interpretation of changes in forest using satellite scanner images. Acta Forestalia Fennica 222: 111 p.

Haralick, R.M., Shanmugam, K. & Dinstein, I. 1973. Textural features for image classification. IEEE Transactions on Systems, Man and Cybernetics SMC-3(6): 610−621.

Härdle, W. 1989. Applied nonparametric regression. Cambridge University Press., Cambridge, England. 323 p.

Heikkonen, J. & Varjo, J. 2004. Forest change detection applying Landsat thematic mapper difference features: a comparison of different classifiers in boreal forest conditions. Forest Science 50(5): 579–588.

Heinonen, T. 2007. Possibilities to aggregate raster cells through spatial optimization in forest planning. Silva Fennica 41(1): 89–103.

Henning, J. & Radtke, P. 2006. Detailed stem measurements of standing trees from groud-based scanning lidar. Forest Science 52(1): 67–80.

Holmgren, J. 2004. Prediction of tree height, basal area and stem volume in forest stands using airborne laser scanning. Scandinavian Journal of Forest Research 19: 543–553.

− & Persson, Å. 2004. Identifying species of individual trees using airborne laser scanner. Remote Sensing of Environment 90(4): 415−423.

− , Joyce, S., Nilsson, M. & Olsson H. 2000. Estimating stem volume and basal area in forest compartments by combining satellite image data with field data. Scandinavian Journal of Forest Research 15: 103–111.

Holmgren, P. & Thuresson, T. 1997. Applying objectively estimated and spatially continuous forest parameters in tactical planning to obtain dynamic treatment units. Forest Science 43(3): 317–326.

− & Thuresson, T. 1998. Satellite remote sensing for forestry planning - a review. Scandinavian Journal of Forest Research 13: 90–110.

− , Thuresson, T. & Holm, S. 1997. Estimating forest characteristics in scanned aerial photographs with respect to requirements for economic forest management planning – a review. Scandinavian Journal of Forest Research 12: 189–199.

Holmström, H., Kallur, H. & Ståhl, G. 2003. Cost-plus-loss analyses of forest inventory strategies based on *k*NN-assigned reference sample plot data. Silva Fennica 37(3): 381–398.

Holopainen, M. 1998. Forest habitat mapping by means of digitized aerial photographs and multispectral airborne measurements. Doctoral Thesis University of Helsinki, Department of Forest Resource Management. 49 p.

− & Lukkarinen, E. 1994. Digitaalisten ilmakuvien käyttö metsävarojen inventoinnissa. Helsingin yliopiston Metsävarojen käytön laitoksen julkaisuja 4. Yliopistopaino, Helsinki. 33 p. (In Finnish).

− & Wang, G. 1998. The calibration of digitized aerial photographs for forest stratification. International Journal of Remote Sensing 19(4): 677–696.

Hyppänen, H. 1999. Eriaikaiset ilmakuvat metsäkuvioiden muutosten tunnistamisessa. Metsätieteen aikakauskirja 2/1999: 155–166. (In Finnish).

Hyyppä, J. & Inkinen, M. 1999. Detecting and estimating attributes for single trees using laser scanner. The Photogrammetric Journal of Finland 16:27–42.

− , Hyyppä, H., Inkinen, M., Engdahl, M., Linko, S. & Zhu, Y. 2000. Accuracy comparison of various remote sensing data sources in the retrieval of forest sand attributes. Forest.Ecology and Management 128: 109–120.

Hyvönen, P., Korhonen, K.T. & Anola-Pukkila, A. 2005a. Metsävaratietojen ajantasaistus NettiMELA:lla. In: Nuutinen, T. & Kettunen, L. (eds.). MELA2005 ja nettisovellukset. Working Papers of the Finnish Forest Research Institute 15: 47–54. (In Finnish).

− , Korhonen, K.T. & Anttila, P. 2005b. Metsävaratiedon jatkuva ajantasaistus metsäsuunnittelua varten -hankkeen väliraportti. Finnish Forest Research Institute, Joensuu. 20 p. (In Finnish).

Ilvessalo, Y. 1927. Suomen metsät. Tulokset vuosina 1921–1924 suoritetusta valtakunnan metsien arvioimisesta. (The forests of Suomi (Finland). Results of the general survey of the country carried out during the years 1921–1924. Communicationes Ex Instituto Quaestionum Forestalium Finlandiae. 192 p. (In Finnish with English summary).

− 1950. On the correlation between the crown diameter and the stem of trees. Communicationes Instituti Forestalis Fenniae 38(2): 1–26.

− 1965. Metsänarvioiminen. WSOY, Helsinki. 400 p. (In Finnish).

Jaakkola, S. 1979. Metsävarojen kartoitustekniikka. University of Helsinki, Department of Forest Mensuration and Management, Research Notes 13. 193 p.

Jackson, R.D., Teillet, P.M., Slater, P.N., Fedosejevs, G., Jasinski, M.F., Aase, J.K. & Moran, M.S. 1990. Bidirectional measurements of surface reflectance for view angle corrections of oblique imagery. Remote Sensing of Environment 32(2-3): 189–202.

Jonsson, B., Jacobsson, J. & Kallur H. 1993. The forest management planning package. Theory and application. Studia Forestalia Suecica. No. 189. 56 p.

Jutila, J. 2006. Laserskannerin käyttö paikannuksessa ja puiden mittauksessa osana metsäkoneen aistinjärjestelmää. Master's Thesis, Helsinki University of Technology, Automation and System Technology. 108 p. (In Finnish).

Juntunen, R. 2006. Puustotiedon laadun vaikutus metsänkäsittelyn optimoinnin tuloksiin – UPM Metsän laserkeilausaineiston ja kuviotiedon vertailu. Master's Thesis, Helsinki University Department of Forest Economics. 87 p. (In Finnish).

Kalland, F. & Harstela, P. 2003. Ratkaisevatko yksityismetsien operatiivisen suunnittelun tarpeet metsäsuunnittelun kehittämisen suunnan? Metsätieteen Aikakauskirja 3/2003: 403–407. (In Finnish).

Kalliovirta, J. & Tokola, T. 2005. Functions for estimating stem diameter and tree age using tree height, crown width and existing stand database information. Silva Fennica 39(2): 227–248.

– , Laasasenaho, J. & Kangas, A. 2005. Evaluation of the Laser-relascope. Forest Ecology and Management 204: 181–194.

Kangas, A. 2006. Design-based sampling and inference. In: Kangas, A. & Maltamo, M. (eds.). Forest Inventory – Methodology and Applications. Springer, Netherlands. p. 13–38.

– & Maltamo, M. 2000a. Calibrating predicted diameter distribution with additional information. Forest Science 46(3): 390–396.

– & Maltamo, M. 2000b. Percentile based basal area distribution models for Scots pine, Norway spruce and birch species. Silva Fennica 34(4): 371–380.

– & Maltamo, M. 2002. Anticipating the variance of predicted stand volume and timber assortments with respect to stand characteristics and field measurements. Silva Fennica 36(4): 799–811.

– , Heikkinen, E. & Maltamo, M. 2002. Puustotunnusten maastoarvioinnin luotettavuus ja ajanmenekki. Metsätieteen Aikakauskirja 3/2002: 425–440. (In Finnish).

Kangas, J., Uuttera, J., Wathén, M., Haapasalo, E., Laamanen, R., Soimasuo, J., Suutarla, T. & Ärölä, E. 2006. Käyttäjien näkökulmia uuden sukupolven metsätietojärjestelmien kehittämiseen. Metsätieteen aikakauskirja 1/2006: 54–59. (In Finnish).

Kansallinen metsäohjelma 2010. 1999. Ministry of Agriculture and Forestry 2/1999. 38 p. (In Finnish).

– 2003. [Internet site]. Ministry of Agriculture and Forestry. Available from: http://www.mmm.fi/kmo/english/. [Cited 20 December 2006].

Kilkki, P. & Päivinen, R. 1987. Reference sample plots to combine field measurements and satellite data in forest inventory. University of Helsinki, Department of Forest Mensuration and Management, Research Notes 19: 209–215.

– , Maltamo, M., Mykkänen, R. & Päivinen, R. 1989. Use of the Weibull function in estimating the basal area dbh-distribution. Silva Fennica 23(4): 311–318.

Kilpeläinen, P. & Tokola, T. 1999. Gain to be achieved from stand delineation in Landsat TM image-based estimates of stand volume. Forest.Ecology and Management 124: 105–111.

King, D. 1991. Determination and reduction of cover type brightness variations with view angle in airborne multispectral video imagery. Photogrammetric Engineering and Remote Sensing 57(12): 1571–1577.

Koivuniemi, J. 2003. Metsiköihin ja paikannettuihin koealoihin perustuvan kuvioittaisen arvioinnin tarkkuus. (The accuracy of the compartmentwise inventory based on stands and located sample plots). University of Helsinki, Department of Forest Resource Management. Publications 36. 160 p. (In Finnish with English summary).

– & Korhonen, K.T. 2006. Inventory by compartments. In: Kangas, A. & Maltamo, M. (eds.). Forest Inventory – Methodology and Applications. Springer, Netherlands. p. 271–278.

Korhonen, K.T. 2002. Metsäsuunnittelun tietohuollon käytäntö ja tutkimus. Metsätieteen Aikakauskirja 3/2002: 509–514. (In Finnish).

Korpela, I. 2004. Individual tree measurements by means of digital aerial photogrammetry. Silva Fennica Monographs 3. 93 p.

– & Anttila, P. 2004. Appraisal of the mean height of trees by means of image matching of digitised aerial photographs. Photogrammetric Journal of Finland 19(1): 23–36.

– & Tokola, T. 2006. Potential of aerial image-based monoscopic and multiview single-tree forest inventory: a simulation approach. Forest Science 52(2): 136–147.

– , Anttila, P. & Pitkänen, J. 2006. The performance of local maxima method for detecting individual tree tops in aerial photographs. International Journal of Remote Sensing 27(6): 1159–1175.

Kovats, M. 1997. A large scale aerial photographic tecnique for measuring tree heights on long-term forest installations. Photogrammetric Engineering & Remote Sensing 63(3): 741–747.

Kujala, M. 1980. Runkopuun kuorellisen tilavuuskavun laskentamenetelmä. Folia Forestalia 441. 8 p. (In Finnish).

Laar, A. & Akça, A. 1997. Forest mensuration. Cuvillier Verlag, Göttingen. 418 p.

Laasasenaho, J. 1982. Taper curves and volume functions for pine, spruce and birch. Communicationes Instituti Forestalis Fenniae 108. 74 p.

– & Päivinen, R. 1986. Kuvioittaisen arvioinnin tarkistamisesta. (On the checking of inventory by compartments. Folia Forestalia 664. 19 p. (In Finnish with English summary).

– , Koivunimei, J. Melkas, T. & Räty, M. 2002. Puuston mittaus etäisyyden- ja kulmanmittauslaitteella. Metsätieteen aikakauskirja 3/2002: 493–497. (In Finnish)

Laiho, J. 2004. Ilmakuvalta automaattisesti muodostettujen segmenttien soveltuvuus metsäsuunnittelun lähtöaineistoksi. M.Sc. thesis. University of Joensuu, Faculty of Forestry. 48 p. (In Finnish with English abstract).

Larsson, M. 1994. The significance of data quality in compartmental forest registers in estimating volume growth and non-optimal losses – A study of final felling compartments in northern Sweden. Swedish University of Agricultural Sciences, Department of Biometry and Forest Management. Report 26. 73 p. (In Swedish with English abstract).

Leblanc, S.G., Bicheron, P., Chen, J.M., Leroy, M. & Cihlar, J. 1999. Investigation of directional reflectance in boreal forests with an improved four-scale model and airborne POLDER data. IEEE Transactions on Geoscience and Remote Sensing, 37: 1396–1414.

Leckie, D., Gougeon, F., Tinis, S., Nelson, T., Burnett, C. & Paradine, D. 2005. Automated tree recognition in old growth conifer stands with high resolution digital imagery. Remote Sensing of Environment 94(3): 311–326.

Lihtonen, V. 1959. Metsätalouden suunnittelu ja järjestely. WSOY, Helsinki. 355 p. (In Finnish).

Liira J., Püssa K. & Peterson U. 2006. The radiance contrast of forest-to-clearcut edges on a medium resolution Landsat Enhanced Thematic Mapper satellite winter image. International Journal of Remote Sensing, 27: p. 2753–2766.

Lillesand, T.M., Kiefer, R.W. & Chipman, J.W. 2004. Remote Sensing and Image Interpretation. 5th edition. John Wiley & Sons, New York. 736 p.

Loetsch, F. & Haller, K.E. 1973. Forest Inventory. Volume I. BLV, Verlagsgesellschaft, München. 436 p.

– , Zöhrer, F. & Haller, K.E. 1973. Forest Inventory. Volume II. BLV, Verlagsgesellschaft, München. 469 p.

Maa- ja metsätalousministeriön metsäsuunnittelustrategia 2001–2010. 2001. Työryhmämuistio MMM 2001:13, Helsinki. 15 p. (In Finnish).

Mäkelä, H. & Pekkarinen, A. 2001. Estimation of timber volume at the sample plot level by means of image segmentation and Landsat TM imagery. Remote Sensing of Environment 77(1): 66–75.

Malinen, J., Maltamo, M. & Harstela, P. 2001. Application of most similar neighbor inference for estimating marked stand characteristics using harvester and inventory generated stem databases. International Journal of Forest Engineering Vol. 12(2): 33–41.

Maltamo, M., Tokola, T. & Lehikoinen, M. 2003. Estimating stand characteristics by combining single tree pattern recognition of digital video imagery and a theoretical diameter distribution model. Forest Science 49(1): 98–109.

– , Mustonen, K., Hyyppä, J., Pitkänen, J. & Yu, X. 2004. The accuracy of estimating individual tree variables with airborne laser scanning in a boreal nature reserve. Canadian Journal of Forest Research 34: 1791–1801.

– , Malinen, J., Packalén, P., Suvanto, A. & Kangas, J. 2006. Nonparametric estimation of stem volume using airborne laser scanning, aerial photography, and stand-register data. Canadian Journal of Forest Research 36: 426–436.

– , Haara, A., Hirvelä, H., Kangas, A., Lempinen, R., Malinen, J., Nalli, A., Nuutinen, T. & Siipilehto, J. 2002. MELA2002 ja kuvauspuiden muodostamisen vaihtoehdot. In: Nuutinen, T. & Kiiskinen, A. (eds.). MELA2002 ja käyttöpuun kuvaus. MELA-käyttäjäpäivä 7.5.2002 Joensuu. The Finnish Forest Research Institute, Research Papers 865: 11–31. (In Finnish).

Mattila, E. 1985. The combined use of systematic field and photo samples in a large-scale forest inventory in North Finland. Communicationes Instituti Forestalis Fenniae 131. 97 p.

McQueen, J. 1967. Some methods for classification and analysis of multivariate observations. Volume 1 of Proceedings of the Fifth Berkeley Symposium on Mathematical statistics and probability. Berkeley, 1967. University of California Press. p. 281–297.

Mehtätalo, L. & Kangas, A. 2005. An approach to optimizing field data collection in an inventory by compartments. Canadian Journal of Forest Research 35(1): 100–112.

– , Maltamo, M. & Kangas, A. 2006. The use of quantile trees in the prediction of diameter distribution of a stand. Silva Fennica 40(3): 501–516.

Moeur, M. & Stage, A. 1995. Most similar neighbor: An improved sampling inference procedure for natural resource planning. Forest Science 41(2): 337–359.

Muinonen, E., Maltamo, M., Hyyppänen, H., & Vainikainen, V. 2001. Forest stand characteristics estimation using a most similar neighbor approach and image spatial structure information. Remote Sensing of Environment 78(3): 223–228.

Næsset, E. 1997a. Determination of mean tree height of forest stands using airborne laser scanner data. ISPRS Journal of Photogrammetry and Remote Sensing 52: 49–56.

– 1997b. Estimating timber volume of forest stands using airborne laser scanner data. Remote Sensing of Environment 61(2): 246–253.

– 2004. Accuracy of forest inventory using airborne laser scanning: evaluating the first Nordic full-scale operational project. Scandinavian Journal of Forest Research 19(6): 554–557.

– & Bjerknes, K-O. 2001. Estimating tree heights and number of stems in young forest stands using airborne laser scanner data. Remote Sensing of Environment 78(3): 328–340.

– , Gobakken, T. 2005. Estimating forest growth using canopy metrics derived from airborne laser scanner data. Remote Sensing of Environment 96(3–4): 453–465.

– , Gobakken, T., Holmgren, J., Hyyppä, H., Hyyppä, J., Maltamo, M., Nilsson, M., Olsson, H., Persson, Å. & Söderman, U. 2004. Laser scanning of forest resources: the Nordic experience. Scandinavian Journal of Forest Research 19: 482–499.

Nilson, T. & Kuusk, A. 1989. A reflectance model for the homogeneous plant canopy and its inversion. Remote Sensing of Environment 27(2): 157–167.

– & Peterson, U. 1994. Age dependence of forest reflectance: analysis of main driving factors. Remote Sensing of Environment 48(3): 319–331.

Nyyssönen, A. 1955. On the estimation of the growing stock from aerial photographs. Communicationes Instituti Forestalis Fenniae 46.1: 1–57. (Reprint)

– 1959. Metsänarvioimistieteellinen tutkimus Suomessa vuosina 1909–1959. Acta Forestalia Fennica 70(5): 1–23. (In Finnish).

Ojala, T. & Pietikäinen, M. 2001. Texture classification. In: Fisher, R.B. (ed.). CVonline – Compendium of Computer vision. Available from: http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/OJALA1/texclas.htm. [Cited: 5 January 2007].

Ojansuu, R., Halinen, M. & Härkönen, K. 2002. Metsätalouden suunnittelujärjestelmän virhelähteet männyn ensiharvennuskypsyyden määrityksessä. Metsätieteen Aikakauskirja 3/2002: 441–457. (In Finnish).

Oksanen-Peltola, L. 1999a. Metsäsuunnittelun tietotarpeet. In: Heikinheimo, M. (ed.) Metsäsuunnittelun tietohuolto. The Finnish Forest Research Institute, Research Papers 741: 13–17. (In Finnish).

– 1999b. Metsävaratiedot. In: Heikinheimo, M. (ed.) Metsäsuunnittelun tietohuolto. The Finnish Forest Research Institute, Research Papers 741: 18–30. (In Finnish).

Olsson, H. 1994. Changes in satellite measured reflectances caused by thinning cuttings in boreal forest. Remote Sensing of Environment 50(3):221–230.

Paananen, R. & Uuttera, J. 2003. Uuden suunnittelujärjestelmän perusratkaisuvaihtoehtoja. In: Saramäki, J, Tikkanen, J. & Heino, E. (eds.). Yksityismetsien suunnittelun uudet tuulet. Seminaari Ylivieskassa 26.11.2003. The Finnish Forest Research Institute, Research Papers 900: 13–17. (In Finnish).

– & Uuttera, J. 2004. Metsävaratietojen tietosisältöjen ja hyötyjen analysointi. Forestry Development Centre Tapio. Helsinki, Finland. 40 p. (In Finnish)

Packalén, P. 2006. Using airborne laser scanning data and digital aerial photographs to estimate forest growing stock. Licentiate thesis, University of Joensuu, Faculty of Forestry. 30 p

– & Maltamo, M. 2006. Predicting the plot volume by tree species using airborne laser scanning and aerial photographs. Forest Science 52(6): 611–622.

Pekkarinen, A. & Tuominen, S. 2003. Stratification of a forest area for multisource forest inventory by means of aerial photographs and image segmentation. In: Corona, P., Köhl, M. & Marchetti, M. (eds.). Advances in forest inventory for sustainable forest management and biodiversity monitoring. Dordrecht, Netherlands: Kluwer Academic Publisher. p. 111–123.

Pellikka, P. 1996. Slope and aspect correction for airborne video camera imagery to improve forest classification in the German Alps. In: Proceedings of the 26th International Symposium on Remote Sensing of Environment, 25–29 March 1996, Vancouver, Canada. p. 463–466.

– 1998. Development of correction chain for multispectral airborne video camera data for natural resource assessment. Fennia 176: 1–110.

– , King, D.J. & Leblanc, S.G. 2000. Quantification and reduction of bidirectional effects in aerial CIR imagery of deciduous forest using two reference land surface types. Remote Sensing Reviews 19:1–4. p. 259–291.

Peuhkurinen, J. 2005. Sävyarvojakaumiin perustuva puustotunnusten estimointi IKONOS-satelliittikuvalta. M.Sc. thesis. University of Joensuu, Faculty of Forestry. 59 p. (In Finnish with English abstract).

Pigg, J. 1994. Keskiläpimitan ja puutavaralajijakaman sekä muiden puustotunnusten tarkkuus Metsähallituksen kuvioittaisessa arvioinnissa. M.Sc. thesis. University of Helsinki, Department of Forest Resource Management. 86 p. (In Finnish).

Pitkänen, J. 2001. Individual tree detection in digital aerial images by combining locally adaptive binarization and local maxima method. Canadian Journal of Forest Research 31(4): 832–844.

Poso, S. 1972. A method of combining photo and field samples in forest inventory. Communicationes Instituti Forestalis Fenniae 76(1): 1–133.

– 1983. Kuvioittaisen arvioimismenetelmän perusteita. (Basic features of forest inventory by compartments). Silva Fennica 17(4): 313–349. (In Finnish with English summary).

– & Kujala, M. 1971. Ryhmitetty ilmakuva- ja maasto-otanta Inarin, Utsjoen ja Enontekiön metsien inventoinnissa. Summary: A two-phase forest inventory based on photo and field plot sampling as applied in northernmost Lapland. Folia Forestalia 132: 40 p.

Pussinen, A. 1992. Ilmakuvat ja Landsat TM -satelliittikuva välialueiden kuvioittaisessa arvioinnissa. M.Sc. thesis. University of Joensuu, Faculty of Forestry. 48 p. (In Finnish).

Rakemaa, A. 2003. Metsäsuunnittelun kehittämisstrategia. In: Saramäki, J, Tikkanen, J. & Heino, E. (eds.). Yksityismetsien suunnittelun uudet tuulet. Seminaari Ylivieskassa 26.11.2003. The Finnish Forest Research Institute, research papers 900: 6–8. (In Finnish).

Ranta, R. 1991. Metsätalouden suunnittelulaskelmat. Tapion Taskukirja, Jyväskylä. 334–337. (In Finnish).

Rasinmäki, J. & Melkas, T. 2005. A method for estimating tree composition and volume using harvester data. Scandinavian Journal of Forest Research 20: 85–95.

Redsven, V., Anola-Pukkila, A., Haara, A., Hirvelä, H., Härkönen, K., Kärkkäinen, L., Lempinen, R., Muinonen, E., Nuutinen, T., Salminen, O. & Siitonen, M. 2002. MELA2002 Reference Manual. Finnish Forest Research Institute. 590 s. Available from http://www.metla.fi/metinfo/mela/index.htm.

Rosenfield, G.H. & Fitzpatrick-Lins, K. 1986. A coefficient of agreement as a measure of thematic classification accuracy. Photogrammetric Engineering and Remote Sensing 52(2): 223–227.

Saksa, T., Uuttera, J., Kolström, T., Lehikoinen, M., Pekkarinen, A. & Sarvi, V. 2003. Clear-cut detection in boreal forest aided by remote sensing. Scandinavian Journal of Forest Research 18(6): 537–546.

Sarvas, R. 1938. Ilmavalokuvauksen merkityksestä metsätaloudessamme. Silva Fennica 48: 2–45. (In Finnish).

Schneider, H. 1999. Aktiivikuvio metsäsuunnittelussa. In: Heikinheimo, M. (ed.) Metsäsuunnittelun tietohuolto. The Finnish Forest Research Institute, Research Papers 741: 81–84. (In Finnish).

Shang, D. & Waite, M.-L. 1991. Utilization of textural and spectral features from Landsat TM imagery for stratifying forest sample plots. University of Helsinki, Department of Forest Mensuration and Management. Research Notes vol. 26.

Siitonen, M. 1993. Experience of the use of forest management models. Silva Fennica 27: 167–78.

Singh, A. 1989. Digital change detection techniques using remotely-sensed data. International Journal of Remote Sensing 10(6): 989–1003.

Solmu. Metsäsuunnittelun maastotyöopas. 2006. Forestry Development Centre Tapio. Helsinki, Finland. 75 p. (In Finnish).

Spencer, R. & Hall, R. 1988. Canadian large-scale aerial photographic systems (LSP). Photgrammetric Engineering and Remote Sensing 54(4): 475–482.

SPSS Inc. 2005. SPSS 12.0.1 Command Syntax Reference. SPSS Inc., Chicago, IL.

Ståhl, G., Carlsson, D. & Bondesson, L. 1994. A method to determine optimal stand data acquisition policies. Forest Science 40(4): 630–649.

Stehman, V. & Czaplewski, R. 1998. Design and analysis for thematic map accuracy assessment: fundamental principles. Remote Sensing of Environment 64(3): 331–344.

Stendahl, J. & Dahlin, B. 2002. Possibilities for harvester-based forest inventory in thinnings. Scandinavian Journal of Forest Research 17(6): 548–555.

St-Onge, B. & Cavayas, F. 1995. Estimating forest stand structure from high resolution imagery using the directional variogram. International Journal of Remote Sensing 16(11): 1999–2021.

Suutarla, T. 1985. Kuvioittaisen arvioinnin päivitys ja tarkkuus. M.Sc. thesis. University of Helsinki, Department of Forest Resource Management. 47 p. (In Finnish).

Tabachnick, B. & Fidell, L. 1989. Using Multivariate Statistics, Second Edition. HarperCollinsPublishers, Inc. 746 p.

Tapion vuositilastot. 2005. Forestry Development Centre Tapio. Helsinki, Finland. 57 p. (In Finnish and in Swedish). Available from: http://www.metsavastaa.net/tiedostot/dokumentit/9823/tvk05_nettiin.pdf. [Cited 5 January 2007].

Taso. Maastotyöopas. 1993. Forestry Development Centre Tapio. Helsinki, Finland. 50 p. (In Finnish).

Tokola, T., Pitkänen, J., Partinen, S. & Muinonen, E. 1996. Point accuracy of non-parametric method in estimation of forest characteristics with different satellite materials. International Journal of Remote Sensing 17(12): 2333–2351.

Tomppo, E. 1992. Multi-source national forest inventory of Finland. Finnish Forest Research Institute. Research Papers 444: 52–60.

Trotter, C. & Dymond, J. 1997. Estimation of timber volume in a coniferous plantation forest using Landsat TM. International Journal of Remote Sensing 18(10): 2209–2223.

Tuominen, S. & Pekkarinen, A. 2004. Local radiometric correction of digital aerial photographs for multi source forest inventory. Remote Sensing of Environment 89(1): 72–82.

– & Pekkarinen, A. 2005. Performance of different spectral and textural aerial photograph features in multi-source forest inventory. Remote Sensing of Environment 94(2): 256–268.

– , Fish, S. & Poso, S. 2003. Combining remote sensing, data from earlier inventories, and geostatistical interpolation in multisource forest inventory. Canadian Journal of Forest Research 33: 624–634.

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

– , Anttila, P. Suvanto, A. & Maltamo, M. 2006. Yksityismetsien metsävaratiedon keruuseen soveltuvilla kaukokartoitusmenetelmillä estimoitujen puustotunnusten luotettavuus. Metsätieteen aikakauskirja 4/2006: 507–519. (In Finnish).

Varjo, J. 1996. Controlling continuously updated forest data by satellite remote sensing. International Journal of Remote Sensing 17(1): 43–67.

– 1997. Change detection and controlling forest information using multi-temporal Landsat TM imagery. Doctoral Thesis, Acta Forestalia Fennica 258. 64 p.

– , Henttonen, H., Lappi, J., Heikkonen, J. & Juujärvi, J. 2006. Digital horizontal tree measurement for forest inventory. Working Papers of the Finnish Forest Research Institute 40. 23 p.

Wang, G., Gong, P. & Biging, G. 2004. Individual tree-crown delineation and treetop detection in high-spatial-resolution aerial imagery. Photogrammetric Engineering and Remote Sensing 70(3): 351–357.

– , Poso, S., Waite, M.-L. & Holopainen, M. 1998. The use of digitized aerial photographs and local operation for classification of stand development classes. Silva Fennica 32(3): 215–225.

Veltheim, T. 1987. Pituusmallit männylle, kuuselle ja koivulle. M.Sc. Thesis. University of Helsinki, Department of Forest Resource Management. 59 p. (In Finnish).

Weszka, J., Dyer, C.R. & Rosenfeld, A. 1976. A comparative study of texture measures for terrain classification. IEEE Transaction on Systems, Man and Cybernetics 6: 269–285

Wilson, D.R. & Martinez, T.R. 1997. Improved heterogeneous distance functions. Journal of Artificial Intelligence Research 6: 1–34.

Wilson, E. & Sader, S. 2002. Detection of forest harvest type using multiple dates of Landsat TM imagery. Remote Sensing of Environment 80(3): 385–396.

Yu, X., Hyyppä, J., Kaartinen, H. & Maltamo, M. 2004. Automatic detection of harvested trees and determination of forest growth using airborne laser scanning. Remote Sensing of Environment 90(4): 451–462.

– , Hyyppä, J., Kaartinen, H., Hyyppä, H., Maltamo, M. & Rönnholm, P. 2005. Measuring the growth of individual trees using multi-temporal airborne laser scanning point clouds. Proceedings of ISPRS Workshop Laser scanning 2005, September 12–14 2005, Enschede, the Nederlands. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXVI (Part 3/W19): 204–208.