Assessment of manual and automated methods for updating stand-level forest inventories based on aerial photography

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Academic dissertation

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ABSTRACT

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Data collection for forest planning in private forestry in Finland is based on periodic, labour-intensive, stand level field inventories. Therefore, to increase guidance for forest owners more cost-efficient methods that replace or supplement field inventories are needed so as to reallocate labour resources. In addition, for active forest owners, up-to-date information is of interest.

The aim of this thesis was to test the applicability of different inventory and updating methods that are based on aerial photography for the regional forest inventory of private forests in Finland. Four approaches were chosen: 1) stand level visual interpretation of changes and simulation of stand development, 2) automatic, stand level interpretation of aerial photographs utilising nonparametric estimation, 3) automatic, photogrammetric estimation of mean height, and 4) automatic, monoscopic identification of individual trees. Approaches 1 and 2 are inventory or updating methods, while approaches 3 and 4 can be considered as components of such methods.

Approach 1 was found to be appropriate for operative use for estates that have not ordered a forest plan, provided that the strict prerequisites for the inventory area are met. The accuracy of approach 2, as such, was not considered to be high enough for forest planning, but this very inexpensive method could turn out to be applicable, if its accuracy could be improved. Approach 3 was based on image matching and would be most useful as a part of other methods, like template matching in multiple images. Although only identification of trees was tested in approach 4, the applicability of whole single tree based inventory method was appraised. Relatively high costs and low accuracy limit the possibilities to use this method, in practice.

Keywords: stand attributes, visual interpretation, nonparametric methods, photogrammetry, single tree detection

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Finally, I want to express my deepest gratitude to my parents for their love and continuous support and to Anna and Eetu for updating my priorities.

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following papers, which are referred to in the text by Roman numerals:

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

II Anttila, P. 2002. Nonparametric estimation of stand volume using spectral and spatial features of aerial photographs and old inventory data. Canadian Journal of Forest Research 32(10): 1849-1857.

III Korpela, I. & 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.

IV Korpela, I., Anttila, P. & Pitkänen, J. 2005. The performance of a local maxima method for detecting individual tree tops in aerial photographs. Accepted to International Journal of Remote Sensing.

Ilkka Korpela and Perttu Anttila jointly developed the research ideas for studies III and IV. In study III, Anttila made the calculations and analysed the data and the both authors contributed to the writing of the manuscript. In study IV, Anttila was responsible for the calculations and analyses of tree detection and Korpela for the tree top positioning. The computer programs for study IV were provided by Korpela and Juho Pitkänen. All authors contributed to the writing of the manuscript.

CONTENTS

1 INTRODUCTION

1.1 Regional forest inventory in private forests in Finland

The objective of a forest inventory system is to yield information on the forest ecosystem for a forest planning system (Pukkala 1994). A forest planning system, in turn, provides information for a decision making system. This whole chain aims at finding a solution that offers maximum utility to a decision maker. Planning or inventory are not necessarily needed for decision making and it is clear that the utility gained by planning should exceed the costs of planning.

In Finland, privately owned forests cover 53% (14.1 Mha) of the total forestry land (Finnish statistical... 2003). In 2003, 1.0 Mha of the privately owned forests were inventoried by Regional Forestry Centres (FC) and 0.1 Mha by Associations of Forest Owners (AFO) (Tapion vuositilastot 2003). These inventories are carried out regionally one village at a time. Hence, a region is inventoried every 10–15 years. Based on the forest inventory data, forest plans are made for private forest owners. On average, in 2003 61% of the private forests had valid plans (Tapion vuositilastot 2003). Apart from forest owners, at least FCs, AFOs, the forest industry, small private forestry entrepreneurs, the Ministry of Agriculture and Forestry, tax authorities and research organisations utilise information collected in regional forest inventories (Oksanen-Peltola 1999).

At present, the FCs use the Solmu planning system, which was introduced in 1996. Solmu data collection is implemented as a stand level field inventory. A stand is a homogenous area with respect to soil, site, growing stock and treatment needs. The average stand size is about 1.5 ha. Before field-work, stand boundaries are delineated on aerial photographs which are typically shot at the scale of 1:30000 on colour-infrared (CIR) film. The delineation is checked in the field and the stand’s basic data (e.g. site description) and information on its growing stock, dead wood, cutting and silvicultural management proposals, biological diversity and other special features are collected. Stand characteristics are estimated subjectively, with the aid of measurements made from subjectively located sample plots. Each tree species and crown layer of growing stock is described by mean values of age, diameter at breast height (dbh) and height, basal area or number of stems, and the proportion of saw log. The volume of growing stock and other deductable, missing attributes are predicted with models. In this kind of field inventory, the accuracy of stand attributes is highly dependent on the skills of the surveyor. Standard errors for volume of growing stock have been between 14-38% (see e.g. I, Haara and Korhonen 2004a).

The information content in the Solmu system is satisfactory, but the age of inventory data should be less than five years (Paananen and Uuttera 2004). A shorter inventory cycle is possible by increasing field-work or by developing inventory methods. Research on how accurate the inventory data for planning should be is lacking. Therefore, it is usually assumed that the present accuracy level of the Solmu inventory is high enough (e.g. Uuttera et al. 2002).

During 2001-2003, the average planning costs in FCs were about 18.6 €/ha of which half is due to field-work (Janne Uuttera, Forestry Development Centre Tapio, 18th Apr 2005, personal communication). This means that ten million euros is spent annually collecting data in the field. The government wants to increase guidance for forest owners and the share of valid forest plans (Kansallinen metsäohjelma 2010 2003). Without increasing total funding, this could be accomplished by making data collection more effective. Consequently, there is an urgent need for more cost-efficient methods to replace or supplement traditional field inventories.

1.2 Updating forest information databases

The basic alternatives for inventory strategies are:

1) periodic field inventory
2) periodic inventory utilising remote sensing for imputing field measurements
3) continuous updating.

In traditional, periodic field inventories, a stand database is up-to-date only after the inventory. In addition, the costs of field-work based inventory can be considered high. The inventory cycle can be shortened by using remote sensing material, like satellite images, aerial photographs and data from airborne laser scanning (ALS). Before recent advances in ALS based inventory, the accuracy of attributes in alternative 2 has been lower than in alternative 1.

In continuous updating, a stand database is kept up-to-date computationally using statistical models. Compared to periodic field inventories, the accuracy of stand attributes is continuously reasonably high. Old inventory data are also effectively utilised. In Finland, large forest enterprises are using continuous updating in the forests they are managing (Korhonen 2002). Stand attributes are estimated in the field after an operation (i.e. a cutting or a silvicultural treatment), after which stand data can be updated computationally. In private forests, continuous updating would be more demanding, mainly because of organisational difficulties (Hyvönen and Korhonen 2003). Namely, forest inventories are conducted and stand databases managed by FCs, but operations are made by forest owners and external contractors. However, by collecting information on operations from different registers of FCs and AFOs and from wood purchasers, continuous updating would also be possible to some extent in private forests (Hyvönen and Korhonen 2003).

For success, realisation of three components in continuous updating must be considered: 1) computational updating, 2) how information on rapid changes (i.e. operations and forest damages) in a forest is obtained, and 3) how to estimate stand attributes after rapid changes or when computational updating is no longer reliable. In all these components, various methods can be applied, which means that information on the accuracies and costs of the methods is needed.

When the growth of stands is simulated using growth models, uncertainty is caused by e.g. errors in the original stand data, errors in the formation of the initial, treewise data for a stand simulator, errors in the growth models, annual variation in growth, forest damages and failures in regeneration (see e.g. Kangas and Kangas 1997, 1999). Errors in original stand data have the greatest influence on the accuracy of updated stand attributes (Ojansuu et al. 2002, Haara and Korhonen 2004b). Consequently, false operations might be proposed in those cases where proposals are based on erroneus data.

Information on rapid changes can be acquired from databases of AFOs and wood buyers – as mentioned above – but it is probable that part of the changes are not in any register. A case in point would be forest damage. There are also errors in registers which should be controlled. Remote sensing can be, however, utilised in change detection. Considerable changes, like clearcuts, can be easily detected, while detection of moderate changes like thinnings, has been more difficult (e.g. Häme 1991, Olsson 1994, Varjo 1996, Hyppänen 1999, Wilson and Sader 2002, Saksa et al. 2003, Yu et al. 2004).

After a cutting or when there are no existing inventory data or its quality is low, stand attributes have to be gathered by a new field cruise or by remote sensing. In principle, the choice of the method should be based on the costs of the method and the losses due to making false decisions because of erroneous stand data. Cost-plus-loss analysis has been proposed as a means to compare different inventory methods (e.g. Ståhl et al. 1994, Holmström et al. 2003, Eid et al. 2004). However, most often the comparisons have been concentrating on the accuracy of different inventory methods and data sources (e.g. Hyyppä et al. 2000, Uuttera et al. 2002, Korpela and Tokola 2005).

The accuracy and productivity of field measurements can be expected to continue to rise. Sample plots are going to be located using satellite positioning and new, more efficient field measurement instruments have been presented (e.g. Kalliovirta et al. 2005). By selecting an optimal measurement strategy, either the accuracy of stand attributes can be maximised in a given time or the measurement time minimised with a certain accuracy level (Mehtätalo and Kangas 2005). Accurate field data forms a solid foundation for both computational updating and remote sensing.

1.3 Aerial photography in forest inventories

The use of aerial photography for purposes of forest inventory has been studied since the 1920s (Loetsch and Haller 1973). In Finland, the first experiments on the use of aerial photography in forest mapping and estimation of growing stock date back to the 1930's (Nyyssönen 1959). Aerial photographs were first used for stand delineation, which continues to be the most important and, in Finland, practically the only application.

Interpretation of aerial photographs in forest inventories may be classified many ways. First, the unit for which the attributes are estimated can be a single tree, a sample plot, a micro stand delineated as a homogeneous image segment, or a stand. Usually in sampling based inventory systems, properties of all visible single trees in a plot have been measured or estimated, while in stand level inventories stand attributes have been determined through estimation of, e.g., mean height, crown coverage and tree species composition. Second, one can separate between visual (i.e. manual) and more or less automatic (i.e. numerical) interpretation. Third, monoscopic images limit the estimation to 2D, whereas photogrammetric techiques allow 3D examination. Fourth, one can predict biophysical properties of forests with variables extracted from aerial photographs or one can actually measure some of them and predict others with the measured attributes.

Digital images are needed for automatic interpretation. Digital aerial photographs are most often obtained by scanning a film, while digital cameras allow direct digital imaging, thus avoiding problems in storing the film and errors due to scanning.

1.3.1 Visual interpretation

The visual estimation or measurement of tree and stand attributes is usually done in 3D, i.e. using instruments that allow stereoscopic viewing. In inventory systems that are based on double sampling (i.e. two phase sampling) the first phase sample can be drawn from aerial photographs. This scheme has been tested and also used operationally, especially in Canada and Australia, i.e. countries with huge land areas (e.g. Spencer and Hall 1988, Biggs and Spencer 1990, Spencer et al. 1997, Gillis 2001), but also elsewhere (Poso 1972, Mattila 1985, Duvenhorst 1995, Hildebrandt 1996, Anttila 1998, Pinz 1999).

In the Nordic countries, visual interpretation at the stand level has dominated research (e.g. Nyyssönen 1955, Nyyssönen et al. 1968, Talts 1977, Åge 1983, Poso 1983, Tiihonen and Virtanen 1983, Ericson 1984, Tomter 1989, Næsset 1991a, 1991b). In Norway, about 70% of the planned area has been interpreted from aerial photographs (Eid et al. 2004). Aasland (2002) noted that the use of old inventory data reduced bias and saved time; time savings in the order of 20-40% can be expected, depending on the intensity of cuttings. He concluded that *a priori* information on stand attributes is more useful than old stand boundaries.

1.3.2 Automatic interpretation at the stand level

Automatic 2D interpretation of aerial photographs at the stand level can be divided into six phases (modified from Campbell 1987):

1) preprocessing
2) stratifying
3) extraction of features
4) selection of reference data
5) estimation of the attributes
6) assessment of the reliability.

Here preprocessing is understood as geometric and radiometric correction. Geometric errors can be corrected in an orthorectification process (see e.g. Lillesand et al. 2004). The pixel values in an image are not only a function of stand properties, they are affected also by film type and processing, exposure falloff, atmosphere and variations in imaging geometry (Holopainen 1998). For this reason, two similar stands in different parts of a photograph may have totally different signals in the image. Radiometric correction aims at reducing the effect of these factors. So far, physical correction models have not been successful because they require too much knowledge about the target to be practically applied. Instead, empirical correction methods for aerial photographs, video images and spectrometer data have been able to alleviate the aforementioned problems (e.g. King 1991, Holopainen and Lukkarinen 1994, Pellikka 1998, Holopainen and Wang 1998a, 1998b, Tuominen and Pekkarinen 2004).

With high resolution remote sensing images – like aerial photographs – a single pixel does not contain any meaningful information. Consequently, features used in classification or estimation have to be extracted from a larger area. Predefined stand boundaries may exist and commonly the aim is to estimate stands' attributes. However, stands are not always homogenous either with respect to stand attributes or image characteristics. In addition, manual delineation is subject to errors. To avoid the effect of vague stand delineation on the estimation of stand attributes, image analysis can be utilised to stratify aerial photographs (e.g. Pekkarinen 2002). The results of Hyvönen et al. (2005) suggested that an image segment could be a better estimation unit than a sample plot. However, shadows, that can be easily separated visually, confuse automatic interpretation. In addition, segments have to be joined to form operational units that can be used in optimisation. Stand level segmentation is, therefore, a promising tool in the automatic estimation of forest characteristics, but needs further development.

Various features based on either tone or texture have been proposed as explanatory variables when predicting stand attributes from aerial photographs. Spectral properties can be described with an average or a vegetation index of an image window, segment or stand. Texture, however, is more difficult to measure, since no unambiguous definition for texture exists. Thus, varying measures have been presented. The most commonly used are statistical variation measures, including first order statistics, like variance of pixel values (e.g. Wang et al. 1998) or a variogram (e.g. St-Onge and Cavayas 1995, Lévesque and King 1999), and second order statistics, like spatial grey-level dependence (Haralick et al. 1973). Inclusion of textural features has usually improved estimation and classification accuracy when using airborne data (e.g. Franklin and McDermid 1993, Wang et al. 1998, Wulder et al. 1998, Franklin et al. 2000, Franklin et al. 2001a, II, Tuominen and Pekkarinen 2005).

Because the co-occurrence matrices for spatial grey-level dependence features are computationally heavy, grey-levels need to be condensed. Variograms, however, can be computed from the original image. There are two approaches on how to utilise variograms as a texture feature (Atkinson and Lewis 2000). First, using the values of a sample variogram directly and second, modeling the variogram and using the model coefficients. The problem with the first approach is that sample variogram values are strongly correlated. However, the second approach has the disadvantage that the form of a variogram can vary significantly from stand to stand and, thus, the automatic fitting of a model is unreliable.

Statistical covariation of stand attributes and image features is described in empirical prediction models. Estimation methods are dealt with in sub-section 1.5. The models are built *ad hoc*, because the relationship will most probably be different given another photography and forest structure. Consequently, reference data (i.e. field data) is needed. Ideally, reference data should be an accurately measured, representative sample. Because field measurements are expensive, the use of existing field data (II) or harvester-collected data (Malinen et al. 2001, Rasinmäki and Melkas 2005) are attractive alternatives.

The final step, both in research and practice, is the assessment of the reliability of the results. The reliability of continuous attributes is usually expressed with measures like the Root Mean Square Error (RMSE), standard error and bias (see e.g. Loetsch et al. 1973). RMSE is a measure of accuracy, and standard error a measure of precision. The reliability of categorical attributes is assessed via an error matrix (i.e. confusion matrix) and measures derived from it, e.g. percentage correct and κ (Campbell 1987). Preferably, part of the reference data should be “saved” to be used as independent test data, because testing with the modelling data overestimates the reliability. If, however, the amount of data is small, cross-validation can be applied.

Examples of automatic interpretation of stand attributes at plot, segment or stand levels using aerial photography can be found in Holopainen and Lukkarinen (1994), Holmgren et al. (1997), Lévesque and King (1999), Hyyppä et al. (2000), Shugart et al. (2000), Tuominen and Poso (2001), II, Tuominen et al. (2003), Tuominen and Pekkarinen (2004, 2005), and Hyvönen et al. (2005).

1.3.3 Automatic interpretation at the tree level

The high spatial resolution of aerial photographs enables estimation at the tree level. Studies that use monoscopic images, i.e. operate in the 2D image domain are discussed in this sub-section, whereas studies on 3D estimation are briefly reviewed in sub-section 1.3.4. As with estimations at the stand level, at the tree level aerial photographs also have to be first scanned and preprocessed. Thereafter, images are segmented to first extract individual tree crowns and then management units (e.g. Gougeon and Leckie 2003) or vice versa (e.g. Anttila and Lehikoinen 2002).

There are various ways to isolate individual tree crowns: 1) Tree tops are detected and crowns segmented using, e.g., a region-growing algorithm. Local intensity maxima (LM) are supposed to represent tree tops (e.g. Dralle and Rudemo 1996, Bolduc et al. 1999, Wulder et al. 2000, Pitkänen 2001, Anttila and Lehikoinen 2002, IV). 2) Synthetic tree crown images representing different crown sizes and shapes and imaging geometries are produced and matched with an aerial image. This technique is called template matching (e.g. Pollock 1999). 3) Crowns are delineated using valley-following algorithms (Gougeon 1995) or by edge detection (Brandtberg and Walter 1999, Wang et al. 2004). In tree crown segmentation, the crowns of a dense tree group are easily merged into one segment. A large crown can also produce several segments. Only dominant and co-dominant trees are visible with a high probability (Korpela 2004), but diameter distribution models can be utilised in the estimation of the number and size of smaller trees (Maltamo et al. 2003).

Crown diameter and dbh are highly correlated for Scots pine (*Pinus sylvestris* L.) and moderately correlated for Norway spruce (*Picea abies* (L.) Karst.) and birches (*Betula pendula* Roth. and *Betula pubenscens* Ehrh.) (Ilvessalo 1950). Thus, crown dimensions can be used in predicting dbh (Kalliovirta and Tokola 2005). Tree height can be predicted with the aid of dbh. Subsequently, tree volume can be calculated using taper curve models (Laasasenaho 1982). Tree species are usually inferred from the spectral properties of a segment (e.g. Meyer et al. 1996, Haara and Haarala 2002), but if the image resolution is high enough texture can also be incorporated into the classification (Brandtberg 1997). One possible estimation chain is illustrated in Figure 1. Stand attributes are obtained as the means and sums of tree attributes. Inventory systems based on single tree detection have been presented and tested by Bolduc et al. (1999), Anttila and Lehikoinen (2002), Gougeon and Leckie (2003), Leckie et al. (2003b), and Korpela and Tokola (2005).

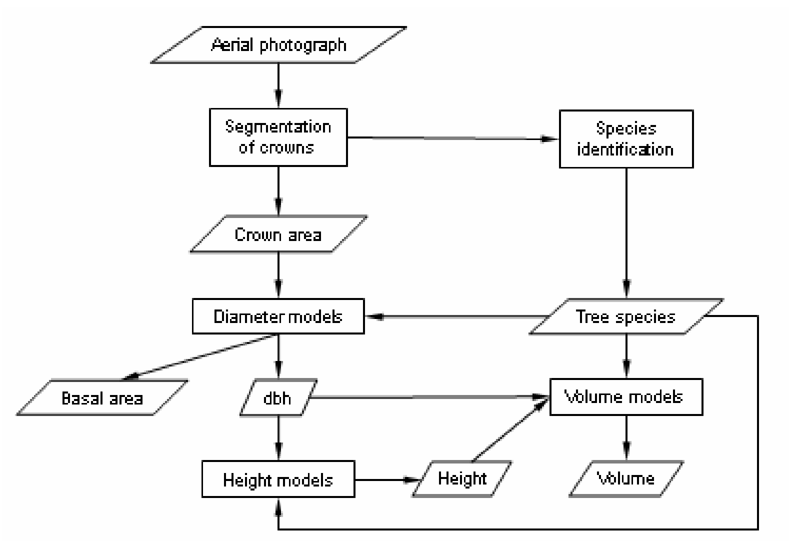

Figure 1. An example of the estimation of tree level attributes in automatic interpretation. Adopted from Anttila and Lehikoinen (2002).

1.3.4 Digital photogrammetry

While the 2D approaches lack vertical information, with stereo or multiple aerial photographic coverage tree height can be measured (e.g. Loetsch and Haller 1973, Korpela 2000). In analogue and analytical workstations, conjugate image points (e.g. crossroads visible in both images) are identified manually. Manual interpretation is, however, time-consuming. In digital photogrammetric workstations this task, called image matching (IM), has been automated. The resulting product from IM is typically a digital surface model (DSM). A thorough introduction to the topic can be found in the textbook by Schenk (1999), which divides the process of IM into the following steps:

1) Select a matching entity in one image
2) Find its conjugate entity in the other image
3) Compute the 3D location of the matched entity in the object space
4) Assess the quality of the match.

IM is an ill-posed task (Schenk 1999). A conjugate entity cannot be sought from the whole image, because the task is computationally too large. Moreover, there may be several matching entities or a corresponding entity does not necessarily even exist. However, by constraining the search space in the image or in the object domain, the task can be solved. IM is successfull in DSM estimation, where terrain is open and well textured.

Conversely, in areas where terrain is rough, texture low or shadows are present, significant errors in matching results can occur (Baltsavias 1999). An excellent example of a difficult surface is the canopy of a heterogeneous, uneven-aged, recently thinned stand of coniferous species (Halbritter 2000). At the same time, one can expect better accuracy in homogeneous, even-aged, dense, old stands of broadleaved species. In addition, small canopy gaps and tree tops are missed and discrete height break-lines present in stand boundaries are smoothed. It has been noted that overall photogrammetrical DSMs are smoother than those obtained by ALS (Baltsavias 1999).

Despite the above-mentioned difficulties, estimation of mean height based on IM has been tried (e.g. Miller et al. 2000, St-Onge and Achaichia 2001, Næsset 2002, St-Onge and Véga 2003, III). The idea is to subtract the height of the digital terrain model (DTM) from the height of a DSM or matched canopy points. When the height above ground for each matched point is determined, the mean height of a certain area can be estimated with a percentile of these heights (cf. Magnussen and Boudewyn 1998). A DTM can be obtained 1) from historical aerial photographs where bare ground is visible (e.g. Miller et al. 2000), 2) using manually measured terrain points in canopy gaps (e.g. Acka 1989) or 3) using ALS (e.g. St-Onge and Achaichia 2001). IM usually leads to the underestimation of tree heights. There are two reasons for this. First, the apexes of cone-shaped conifer trees are not visible on aerial photographs, because the diameter of a shoot is smaller than the resolution of the image (Kovats 1997). Second, the matched points are systematically below tree tops and even the ground, and not at the level of tree tops, as desired (III).

Single tree height can be estimated by subtracting the height of the DTM from the height of the tree apex. The tree apex can be positioned stereoscopically (St-Onge et al. 2004) or by using template matching in multiple images (e.g. Korpela 2000, Tarp-Johansen 2002, Korpela 2004). Sheng et al. (2001) fused IM and geometric-optical tree models to overcome the problems in IM of forests.

1.4 Other remote sensing methods

Since the launch of Landsat 1 in 1972, research on the use of medium resolution (10-80m) optical satellite images has been active. Yet, the results, from the point of view of forest planning, have not been convincing, because, e.g., availability of cloud free images, early saturation of reflectance, low spatial resolution and the small effect of forest operations, other than clearcuts, on the measured reflectance (Holmgren and Thuresson 1998, Anttila 1999, Hyyppä et al. 2000, Franklin 2001, Hyvönen 2002). Thus, it can be concluded that medium resolution satellite images are not suitable for forest planning at the estate level.

Lately, a variety of high resolution passive sensors, both airborne and satellite-borne, have entered markets. These data can be interpreted by using the same methods as used for aerial photographs, but they may also possess some extra virtues. E.g., because of the high imaging altitude and the narrow field of view, radial displacement is constant within a satellite image, and multispectral scanner images have higher spectral resolution than aerial photographs. The high price and poor availability of images have delayed the operational use of high resolution sensors. According to internet sources, the price of high resolution satellite images is ca. 0.2-0.4 €/ha (Alex's Remote Sensing… 2004, European Space Imaging... 2004, OrbView-3... 2005). Estimation of forest inventory parameters using various high resolution sensors have been studied by, e.g., Franklin and McDermid (1993), Gougeon (1995), St-Onge and Cavayas (1995), Pollock (1999), Hyyppä et al. (2000), Wulder et al. (2000), Leckie et al. (2003b), and Wang et al. (2004) with spectrometer images, and by Maltamo et al. (2003) with video camera images. Hitherto, only a few publications on the use of actual high resolution satellite data for forest inventory purposes exist (e.g. Franklin et al. 2001b, Astola et al. 2004, Peuhkurinen 2005).

Active sensors are not as dependent on the weather conditions or time of day as the passive sensors are. Passive sensors also suffer from early saturation of reflectance (Nilson and Peterson 1994). Yet another advantage of active sensors is that they measure the distance to the target instead of just measuring a mixture of radiation reflected from the target, radiation scattered by atmospheric haze and radiation that is first scattered and then reflected from the earth (Campbell 1987). However, the accuracy of satellite-borne microwave radar based inventory at the stand level has been low (e.g. Hyyppä et al. 2000, Pulliainen et al. 2003). Slightly higher accuracies have been observed with airborne microwave radar (e.g. Wang and Dong 1997, Fransson et al. 2000, Hyyppä et al. 2000).

ALS holds high promise for forest inventory, and the research on the topic has been active (Lim et al. 2003b, Næsset et al. 2004). Prediction of mean height, basal area and stand volume is at least as accurate as in conventional field inventories (e.g. Næsset 1997a, 1997b, Magnussen and Boudewyn 1998, Hyyppä and Hyyppä 1999, Hyyppä and Inkinen 1999, Means et al. 2000, Lim et al. 2003a, Maltamo et al. 2004). The two estimation approaches used are a single-tree-based (e.g. Hyyppä and Inkinen 1999, Hyyppä et al. 2001) and a sampling-based method (e.g. Means et al. 2000, Næsset 2004b), the latter one being already in operational use (Næsset 2004a, 2004b). The first one requires high laser point density, whereas in the second one the density can be sparser. Aerial photographs are usually needed for the determination of tree species (e.g. Næsset 2004b). By using high density ALS, even separation of Scots pine and Norway spruce (Holmgren and Persson 2004), or the estimation of growth and detection of thinnings (Yu et al. 2004) may be possible. The price of ALS is 2-5 €/ha depending on the size and shape of the area (Yu et al. 2004).

1.5 Relating field and remote sensing data

The dependence between biophysical properties of forests and remotely sensed intensity of radiation can be modeled either physically or empirically. So far, empirical models have been more successful. Double sampling (e.g. Poso et al. 1999) and linear regression models (e.g. Holmgren et al. 1997) are classical approaches, but, recently, nonparametric regression methods (e.g. *k*-nearest-neighbours estimation) and artificial intelligence methods (e.g. neural networks) have been popular both in research and practice (e.g. Kilkki and Päivinen 1987, Tomppo 1992, Holopainen and Lukkarinen 1994, Hyyppä et al. 2000, Franco-Lopez et al. 2001, Holmström 2002).

The advantages of nonparametric regression include: 1) No assumptions for the shape of underlying distributions are needed and nonlinear dependence can also be described (Altman 1992). Remote sensing based data are often non-normally distributed (e.g. Varjo 1996) and the relationships are nonlinear (e.g. Nilson and Peterson 1994). In addition, in real, complicated systems, visible relations are not always noticeable between variables. Nonparametric methods, however, may find hidden structures. 2) A variety of tree and stand attributes are of interest in a typical plot or stand level inventory. When all the attributes are predicted at the same time, as is possible with nonparametric methods, the complex relationships between predicted attributes are retained (Moeur and Stage 1995). 3) When all estimates come from reference data, no unrealistic estimates, i.e. extrapolation, can exist (Moeur and Stage 1995). With a proper selection of smoothing parameters (i.e. number of neighbours or bandwidth), nonparametric methods also preserve almost the original range of variation.

In nonparametric regression methods, an estimate of a dependent variable at a certain value of an independent variable is a weighted average in the neighbourhood of that value (Altman 1992). The more similar the independent variables (later referred to as indicator attributes) of a target observation and a reference observation are, the higher the weight is. The weight depends on the distance between the observations in the space of indicator attributes. Atkeson et al. (1997) presented various weighting functions, also called kernel functions, and concluded that the choice of the function form is usually not critical.

A variety of distance functions has been proposed (see e.g. Atkeson et al. 1997, Wilson and Martinez 1997). The simplest way to determine the distance between neighbouring observations is to use unweighted Euclidean distance. However, by weighting indicator attributes, their relevance can be taken into account. The weights can be derived heuristically (e.g. Haara et al. 1997), from an inverse covariance matrix of indicator attributes (the so-called Mahalanobis distance, see Wilson and Martinez 1997) or from regression between dependent and indicator attributes (the so-called regression transform distance, see Tokola et al. 1996) to mention a few. In real applications, the number of attributes may be considerable, leading to large weight matrices when calculating regression distance. The attributes may also be highly correlated. This is why Moeur and Stage (1995) introduced the Most Similar Neighbour (MSN) distance function. In MSN, the weighting matrix is a product of the matrix of canonical coefficients of the indicator attributes and a diagonal matrix of squared canonical correlations. Therefore, if only significant (uncorrelated) canonical variates are retained, the size of the weighting matrix can be reduced without losing much predictive information.

A disadvantage of the nonparametric methods is that they are data dependent. Reference data are also needed in the application stage. Another drawback would be that unbiased estimates cannot be guaranteed. E.g., the used reference stands must correspond to target stands. Furthermore, the qualifier ”nonparametric” is somewhat fallacious, since at least the parameter values in the weight function and the number of neighbours have to be decided upon before the analysis. With MSN especially, a linear correlation between dependent and indicator attributes is assumed (Moeur and Stage 1995).

1.6 Objectives of this thesis

The starting point of this thesis lies in tactical forest planning for private forests in Finland. It is anticipated that the life cycle of the present planning system will end in 2008, so the design for a new planning system has started (Paananen and Uuttera 2003). This thesis was partly done as a part of this development work. The new system will most probably lean on high resolution remote sensing, like aerial photography and ALS, and more effective use of existing inventory data. In practice, aerial photographs are needed for stand delineation and old inventory data exist for a large portion of the private forest areas of Finland. Thus, it can be assumed, that aerial photographs and old inventory data are existing data sources and that they are available for a new inventory.

The aim of this thesis was to test the applicability of different inventory and updating methods, which are based on aerial photographs, for the regional forest inventory of private forests in Finland. For the utilisation of aerial photographs, four approaches were chosen of which approaches 1 and 2 are inventory or updating methods, while approaches 3 and 4 can be considered as components of such methods:

1) Stand level visual interpretation and simulation of stand development (I, Uuttera et al. 2002, Anttila 2003, Uuttera 2003).
2) Automatic, stand level interpretation of aerial photographs utilising nonparametric estimation (II, Uuttera et al. 2002).
3) Automatic photogrammetric estimation of mean height (III).
4) Automatic identification of individual trees in 2D (IV).

Results from non-refereed publications (Uuttera et al. 2002, Anttila 2003, Uuttera 2003) are also presented here, because they are a direct continuum to studies I and II.

2 MATERIAL

The study areas were located in central Southern Finland (Figure 2). In studies I and II, the Solmu inventory data from private forest estates from Viippero in the municipality of Suonenjoki were used, whereas field plots in Hyytiälä, in the municipality of Juupajoki, were used for the field data in studies III and IV. The data set from Viippero was supplemented with data from the Mustinmäki planning area in the study of Uuttera et al. (2002). Mustinmäki is situated 50 km to the East of Viippero. The growing stock in Mustinmäki was older and more spruce dominated than in Viippero. For a more specific description of Mustinmäki, see Hyvönen (2002).

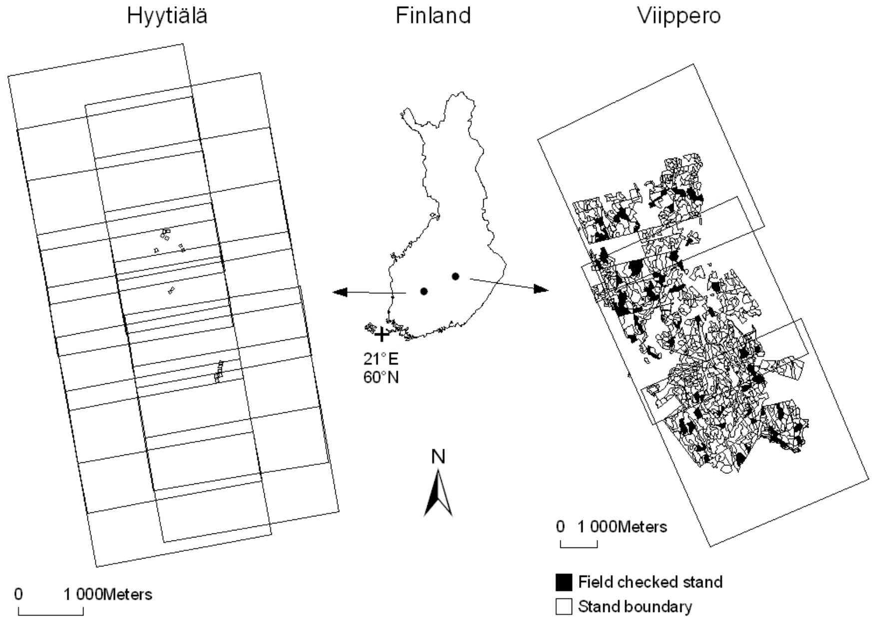

Figure 2. Study area of studies I and II (right) and field plots of studies II and IV (left). The coverage of aerial photographs for both areas is also indicated.

The main tree species in Viippero were Norway spruce and Scots pine. Almost half of the forest land was spruce-dominated, moist upland forest of the *Myrtillus* site type and around one quarter was rather dry upland forest of the *Vaccinium* type, dominated by pine. The peatland proportion was ten percent. Approximately 40% of the forest land was occupied by young stands and less than one third by both seedling or sapling stands and mature stands.

The area was surveyed by FC in 1999, according to the Solmu system, as part of a regional inventory. To determine the accuracy of the inventory, 66 randomly sampled stands were field checked by placing 5–9 sample plots systematically in each stand. The previous inventory in the same area was carried out in 1987 according to the TASO system (see I), also by FC.

In studies III and IV, field plots from a thinning experiment from Hyytiälä were used. The experiment was founded and is managed by the University of Helsinki (Korpela 2004). All 15 plots provided the field data for study III, but for study IV only seven quite recently thinned plots were chosen. The data are described in detail in Hyytiala_2002_Documentation (2002) and in study III.

The aerial photographs of Viippero were taken in 1999 (Table 1). The whole area was covered by three photographs, and there was no stereo overlap. The scale of the photography was larger than normal and the photographs were taken in the same year as the field inventory was conducted. Standard photography for forest planning takes place 1-3 years before a field inventory. The timing of the photography was not optimal, as the best time would be early or mid-summer, when there is enough light, shadows are short and the leaves are not yet yellow.

In 2002, the Hyytiälä area was photographed at different scales and with different film materials, the scales ranged from 1:6000 to 1:30000 (Hyytiala_2002_Documentation 2002). For studies III and IV, the photography scale 1:12000 was chosen as a good compromise, because single trees are well discernible, but individual branches of the trees do not contribute too much to the texture (Table 1). The number of images used in studies III and IV was thirteen and twelve, respectively. The timing of this photography was exceptionally early, but the trees were already in full leaf.

3 METHODS

3.1 The VISU method

In 2000, two procedures for updating stand level inventory data applying a stand simulator and monoscopic visual interpretation of orthorectified images were developed and tested (I). One was found suitable for further research, and in 2001 the method was named VISU and revised so that difficult cases, like stands regenerated during the planning period, were no longer updated, but directed to field check (Uuttera et al. 2002). In 2002, only minor modifications to the VISU-method were made and the reliability and time consumption were re-estimated (Anttila 2003). Finally, in 2003, wide tests to evaluate the feasibility of the method for operational use were carried out by the Forestry Development Centre Tapio (Uuttera 2003). Because the interpretation skills of individuals vary, the results of several interpreters are compared in sub-section 4.1.

Table 1. Image data.

Study	I & II	III & IV
Scale	1:20000	1:12000
Date of photography	Sep 26, 1999	May 27, 2002
Time of photography (GMT+2)	14:10	10:00
Forward overlap, %	20	70
Side overlap, %	-	60
Sun azimuth, °	198	117
Sun elevation, °	22	37
Camera	Wild RC30	Wild RC20
Focal length, mm	153.19	152
Film type	CIR	CIR
Nominal pixel size, cm	50	16.8

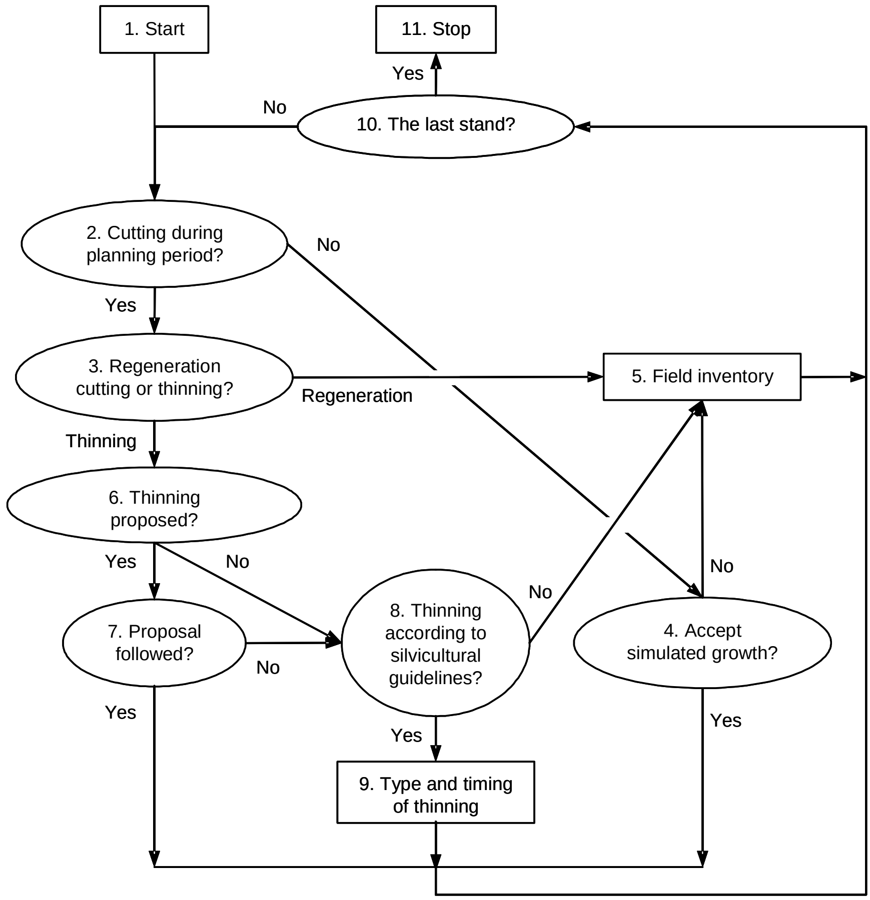

Figure 3. Photo interpretation in the VISU-method in 2003.

The VISU-inventory begins with similar work phases as the Solmu inventory. First, existing stand attributes and boundaries are retrieved from a stand database. Second, the boundaries are overlaid on the new orthophoto and corrected manually on the screen. In VISU, development of stands (without cuttings) is then simulated using a stand simulator. The MELA simulator (Siitonen et al. 1996) was utilised in all the tests. This is the starting point of the actual VISU procedure.

The photo interpretation of the revised VISU procedure is shown in Figure 3. Practically, stands are visually classified into four categories: 1) stands where simulated growth can be accepted, 2) stands which have been thinned as proposed in the previous field inventory, 3) stands that have been thinned according to silvicultural guidelines (Hyvän metsänhoidon suositukset 2001), but not according to cutting proposals, and 4) stands that need to be surveyed in the field. The field inventory procedure is the same as in Solmu.

With Figure 3, few specifications must be made. In steps 2 and 3, forest use declarations and old management proposals are also used to detect cuttings made after photography and thinnings from the beginning of the previous planning period. In step 3, all the stands, where a regeneration cutting has been made, are classified to be field checked. In addition, if a forest use declaration has been given after the photography or an urgent thinning has been proposed in the previous plan, a stand has to be checked in the field. In step 7, the intensity and timing of the thinning are considered. If it seems likely that one or the other does not match, the intensity is considered in step 8. If the stand has been thinned according to silvicultural guidelines, the type and timing of the thinning are interpreted. The first commercial thinning is separated from the subsequent thinnings, because the thinning removal is calculated based on the number of stems in the first thinning and on the basal area in the following thinnings. Timing is interpreted in classes of five years.

After the interpretation, the development of the thinned stands (categories 2 and 3) is simulated again, this time the thinnings are also simulated. These data are checked again, visually, to see if the updated data can be accepted.

New cutting proposals based on updated stand attributes are optimised in MELA. The optimisation problem in the tests was to maximise the net income of the second five-year period so that the income of the first period would be equal or greater than the income of the second period.

3.2 Automatic interpretation at the stand level

Numerical, stand level interpretation of aerial photographs using the nonparametric *k*MSN method was tested during 2000-2002 (II, Uuttera et al. 2002). This method was introduced by Muinonen et al. (2001) and revised in II. In a subsequent study, material was further supplemented by the Mustinmäki study area and a wider range of stand attributes, cutting proposals and proposals of silvicultural work were estimated (Uuttera et al. 2002).

The estimator of the stand attribute (i.e. design attribute) y in stand u was

$$\hat{y}_u = \frac{\sum_{j=1}^{k} w_{uj} y_j}{\sum_{j=1}^{k} w_{uj}} \tag{1}$$

where subindex j refers to a neighbouring stand (i.e. reference stand) in the attribute space, k is the number of neighbours and w is a weighting factor. Here, w was inversely dependent on the distance D between the stands in the space of indicator attributes (equation 2). Constant a was added to the denominator in order to avoid division by zero. The magnitude of this constant is insignificant, if the distances between the k nearest neighbours do not vary much. Here, the value of a was 1.

$$w_{uj} = \frac{1}{D_{uj} + a} \tag{2}$$

The similarity of stands was measured with the MSN distance function:

$$D_{uj}^2 = (\mathbf{X}_u - \mathbf{X}_j)\mathbf{\Gamma}\mathbf{\Lambda}^2\mathbf{\Gamma}'(\mathbf{X}_u - \mathbf{X}_j)' \tag{3}$$

where **X** is a matrix of indicator attributes, $\mathbf{\Gamma}$ a matrix of canonical coefficients of the indicator attributes, and $\mathbf{\Lambda}^2$ a diagonal matrix of squared canonical correlations. As indicator attributes, stand level spectral and textural values from aerial photographs and old inventory data were used. The spectral features were median values from three original, and one ratio, channels. The last one was calculated as a ratio of red and green channels corresponding to infra-red and red wavelengths.

Empirical semivariances (i.e. sample variograms) were assumed so as to describe the texture of stands. A geostatistical modelling programme, *gstat*, was utilised in the calculation of semivariances (gstat home page 2004). The pixel values of each stand were extracted from ratio images and used as input for *gstat*. Various combinations of input parameter values were tried and the values used in the final estimations are presented in Table 2. In II, semivariances were calculated in the direction of the sun's azimuth, and in the study of Uuttera et al. (2002) variograms were omnidirectional. Semivariances were calculated with the classical variogram estimator (Cressie 1991).

The following attributes were selected from old inventory data: site type, soil type, mean age, mean volume and volumes of pine, spruce and deciduous species. Attributes describing growing stock were not updated, because information on cuttings and silvicultural operations that were carried out during the planning period was not available.

3.3 Estimation of mean height through digital photogrammetry

Estimation of mean height by applying the IM of aerial photographs was tested in III. A commercial software package was utilised to compute ”mass points”, i.e. matched canopy points with 3D object coordinates. The algorithm is based on feature-based matching (IMAGINE OrthoBASE... 2001). First, point features from both images in a stereo pair are extracted using the Förstner interest operator (Förstner and Gülch 1987). Second, image patches of interest points are compared between the two images along epipolar lines and a feature pair that have attributes with the highest cross-correlation is recognized as a match. Third, ground coordinates for matched points are computed using space forward intersection. Fourth, the mass points are exported.

The height above ground was calculated for each mass point by subtracting the value of the DTM from the elevation of the mass point (III). An ideal, accurate DTM for each plot was interpolated from the known 3D positions of tree butts.

Table 2. Parameter values of *gstat* in the studies.

Parameter	Explanation	II	Uuttera et al. (2002)
cutoff, m	the maximum distance at which pairs of data points will be considered for inclusion in sample variogram estimates	10	6
width, m	the step size of distance intervals for sample variogram estimates (i.e. lag)	1	1
alpha, °	direction in the x, y –plane	18	0
tol_hor, °	horizontal tolerance	10	90

Seven percentiles of the height distribution of mass points were tested as an estimator of mean height (III). The reliability of estimates was examined with three measures, namely the mean of the residuals (systematic error), standard deviation of residuals (precision) and the correlation of estimated and reference heights (ability to model the variation in mean height). The effects of the location of a plot in a stereo model, image overlap, tree species and stand treatment on reliability were tested.

3.4 Semi-automatic detection of tree tops

The performance of a local maxima (LM) based method for detecting image positions of individual tree tops was tested and a new method for the assessment of the detection accuracy for 2D tree detection image analysis methods was developed in IV. In the LM method, the images were first smoothed using a Gaussian kernel and subsequently binarized to mask out the dark areas between bright crowns. In the smoothed images, local intensity maxima in the infrared channel were regarded as tree top candidates. The detection method is described in detail in Pitkänen (2001).

To link the LM with true 3D tree top positions, a procedure that utilises inclusion testing and ray-tracing was developed (IV). With it, each LM could be classified as a commission point (no matching tree), a unique hit (one-to-one match) or a multiple hit (more than one LM per tree). Multiple hits were further classified as a closest hit (closest to the true tree top) or as an extra hit (other multiple hit). Likewise, the trees were divided into three classes: missed, uniquely detected and over-detected.

A total of 45 different image-plot combinations represented various camera-object-sun geometry. This allowed one to study the effects of viewing angle and illumination on accuracy. The plots in each image were divided into four illumination classes depending on the location in the image (IV).

Smoothing and binarization were both controlled with one parameter (IV). To study the effects of parameterisation, a range of parameter values were tested. From each image-plot combination, the most accurate case was selected for an analysis of tree top positioning accuracy. For unique hits, the displacement from the true tree top and further mean error vectors, their norms and RMSEs were calculated. In order to study systematic positioning errors due to the imaging geometry, a regression model was adopted. Finally, the proportion of detected, corresponding trees in the image pairs was calculated, so as to study if LM could potentially be used as a feature detector in stereo IM for canopy surface modelling.

4 RESULTS

4.1 The VISU method

As expected, differences in the characteristics of the study areas, quality of old inventory data and interpreters' skills caused variability in the results (I, Uuttera et al. 2002, Anttila 2003, Uuttera 2003). At best, the VISU-method can be as accurate as field inventory, on average, whereas the highest RMSEs suggest the method is not useful in forest inventory for management planning (Table 3). Bias is caused by biased initial data and incorrect interpretations. In these tests, stand volume bias was between -15 and 20% (negative values being over-estimates and positive under-estimates).

Generally, cutting proposals from a MELA-optimisation seem to be feasible, but proposals for silvicultural work should be given during operational field-work. In 2002 and 2003, proposals were evaluated in the field (Table 4). A proposal was acceptable if it could be considered feasible according to silvicultural guidelines (Hyvän metsänhoidon suositukset 2001).

Photo interpretation was 5-20 times faster than field-work (Anttila 2003). For this reason, the proportion of field-work affects work productivity the most. The proportion has varied from 23% to 86% of the total area (Table 5). Proportions of categories are mostly determined by the distribution of stand development classes, but also by the personal skills of an interpreter.

Table 3. Reliability of updated stand volume. Note that in 2003 updated stand attributes were compared to a Solmu field inventory. Thus, the actual reliability may be higher.

Test year	RMSE, %	Bias, %	# stands	# interpreters
2000	25.4 - 50.9	0.5 - 19.9	37	6
2001	35.7	15.1	22	1
2002	29.1	2.3	29	1
2003	18.7 - 38.7	-3.2 - -15.3	39-88	4

Table 4. Acceptable cutting proposals in field-checks.

FC	Test year	Evaluated stands	Proposal acceptable, %
Pohjois-Karjala	2002	16	87.5
Kainuu	2003	192	89.6
Etelä-Savo	2003	175	65.7
Lounais-Suomi	2003	349	95.4
Häme-Uusimaa	2003	221	85.5

Table 5. Proportions (%) of the categories in the study areas. GROWTH_OK = Simulated growth accepted, PROP_THIN = Thinning interpreted as proposed in a previous field inventory, THINNING = Thinning interpreted, FIELD = Directed to field inventory.

Year	GROWTH_OK	PROP_THIN	THINNING	FIELD	# interpreters
2001	48.6	19.7	8.6	23.1	1
2002	17.1 - 37.2	5.3 - 47.5	0.6 - 9.6	33.4 - 69.1	5
2003	5.0 - 39.3	2.1 - 28.5	2.3 - 8.6	40.8 - 85.9	4

In 2002, the productivity with the VISU-method was 2-4 times higher than with the Solmu field inventory (Anttila 2003). The productivity varied from 9.6 to 21.4 ha/h including the following phases: search and analysis of the forest use declarations, photo interpretation, simulation of the development of thinned stands, and field-work. Without field-work, productivity varied between 27.0 and 110.2 ha/h. In 2003, productivity without field-work amounted to only between 8.5 and 20.4 ha/h. Comparison is, however, hampered by the fact, that different phases were included in the tests. In the latter test, the phases were search and analysis of the forest use declarations, simulation of growth, overall examination of study area, photo interpretation and generation of new cutting proposals. Because simulation of growth, overall examination and generation of new cutting proposals were not included in the earlier test, the real productivity is lower than stated above. Nevertheless, it is evident that the range for productivities is large.

4.2 Automatic interpretation at the stand level

The highest accuracy was achieved when both spectral and spatial information and old inventory data were used (II). The features extracted from aerial photographs were not very strong explanators, since old inventory data alone were better indicator attributes. Cross-validation was used in II. However, to obtain a more realistic understanding of the performance in real circumstances, the mean volumes for 37 field checked stands were estimated using 544 reference stands. When the best combination of indicator attributes was used, the RMSE was 32.2% and bias 19.6%. The underestimation was due to underestimation in stand level field inventory. True mean volumes were calculated from the field-check data.

For two study areas, multiple design attributes were simultaneously estimated. In addition to mean volume, age, mean diameter, mean height, basal area and volume of pine, spruce and deciduous species were also estimated (Table 6). The averages of these results are reported in the study of Uuttera et al. (2002). In Viippero, almost the same field-data were used in estimation as above. However, the accuracy was now lower. Apparently, the reason is that with multiple design attributes the weight (equation 2) is no more optimal for any single attribute. Thus, the reliability of estimation decreases as the number of design attributes is increased.

The highest accuracy in estimating multiple attributes was achieved when spectral information and old inventory data were used. The use of texture somewhat lowered the accuracy. In Mustinmäki, the accuracy of design attributes in reference data was higher than in Viippero (Table 6). Consequently, the estimates are less biased.

The RMSE dropped quickly when k was increased, but stabilised after 4-7 neighbours, in II. In comparable studies, the optimal number of neighbours has varied between 3 and 10 (Holmström et al. 2001, Muinonen et al. 2001, Tuominen and Poso 2001). Based on these results, k was fixed to seven in the later study (Uuttera et al. 2002).

Estimation accuracy was clearly improved when the smallest and elongated stands with complex topology were left out (II). In Mustinmäki, a similar trend was noticed. When the minimum stand area was raised from zero to one hectare, the RMSE dropped almost 7 %-units.

Table 6. Reliability of estimation with multiple design attributes in Viippero ($n_{reference}$ = 547, n_{target} = 37) and Mustinmäki ($n_{reference}$ = 632, n_{target} = 22).

Attribute	Error, %	Viippero	Mustinmäki
Age	RMSE	12.7	12.4
	bias	6.4	-3.8
Mean diameter	RMSE	30.1	14.5
	bias	26.1	8.4
Mean height	RMSE	19.5	16.2
	bias	15.3	13.7
Basal area	RMSE	29.3	21.4
	bias	18.5	8.3
Mean volume	RMSE	38.8	31.7
	bias	27.6	19.4
Volume of pine	RMSE	75.5	58.6
	bias	35.9	22.8
Volume of spruce	RMSE	54.9	40.5
	bias	22.9	19.0
Volume of deciduous	RMSE	92.7	66.4
	bias	20.2	14.6

If the reference data does not correspond to target stands, the variation in values of design attributes in target stands can not be covered. In Viippero, the mean of mean volume in field-checked stands was 204 m^3ha^{-1} but in reference stands only 135 m^3ha^{-1}. In Mustinmäki, the figures were 203 m^3ha^{-1} and 163 m^3ha^{-1}, respectively. In addition, the mean volume was underestimated in reference area, by 14% in Viippero and by 8% in Mustinmäki. Together, these factors lead to underestimation (Table 6).

Cutting proposals and proposals of silvicultural work were estimated for 917 stands in Mustinmäki using 935 stands in Viippero as reference data. Estimated proposals were compared to subjectively given proposals in the Solmu-inventory. Only 55% of the cutting proposals (thinning, regeneration, no cuttings) and 72% of the proposals for silvicultural work (cleaning of sapling stand, no silvicultural work) were similar to those given in the field.

4.3 Estimation of mean height through digital photogrammetry

The mean height percentile estimator was chosen based on the correlation measure, *r* (III). The highest value of *r* was reached with the 60^{th} percentile of mass points, though the 50^{th} and 75^{th} percentiles were very close both in *r* and the standard deviation of 10x10 m window level residuals of mean height, SD(ΔH_{ij}). Næsset (2002) found the 75^{th} percentile to be the most precise estimator. Here, it was a less biased estimator than the 60^{th}

percentile, but a precision as high as possible was still considered most important in choosing the estimator.

Every mean height estimate was an underestimate (III). The average underestimation was 4.2 m when image overlap was 60% and 2.7 m when the overlap was 70%. Underestimation is due to the fact that the mass points mainly hit below the elevation of the tree tops (Figure 1 in III). This again arises from the way the interest points are extracted. The basic idea of extracting distinct points in an image is to identify areas with high variance (Schenk 1999). With medium-scale aerial photographs, in a forested landscape, these areas are usually not on the tree top but on the edge of a light tree crown and dark ground (Figure 4).

Estimation of mean height was more reliable by all three measures when stereo pairs with 70% overlap were used, compared to 60% overlap (III). The precision of the estimator was, on average, 2.2 m using images with 60% overlap and 1.1 m using 70% overlap. The average correlations were 0.42 and 0.70, respectively. At plot-level, the RMSE was 2.8 m (16.2%) when the overlap was 70%. With the 90th percentile the accuracy was even higher, 1.1 m (6.2%).

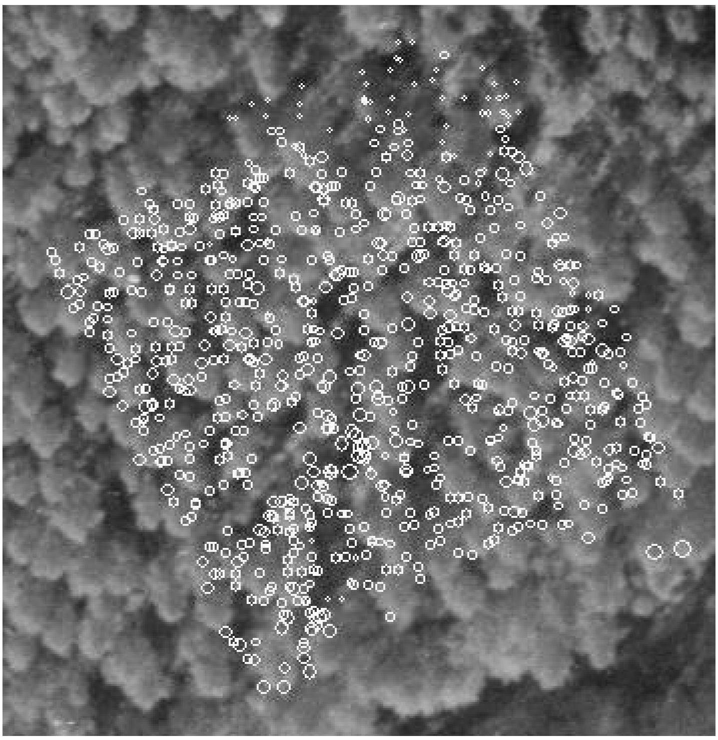

Figure 4. Mass points of one plot superimposed on an aerial photograph. Circle width denotes height above ground. Image by Ilkka Korpela. Copyright FM-kartta International Ltd., Helsinki. Used with permission.

The estimation of the height of well matched mass points becomes more uncertain, when the overlap is increased. However, the proportion of false matches increases if the corresponding image patches in an image pair appear very different. The same phenomenon can also be visually detected: it may be hard to see a tree in stereo, if the tree is viewed, e.g., straight above in one image and heavily slanted in another. According to these results, the effect of the second factor on the accuracy of estimation of mean height is more serious than the effect of the first one. Consequently, the overlap should be at least 70%, should the method be used in practice. An increase in focal length would probably affect the reliability in a similar way, although Næsset (2002) found no effect between focal lengths of 153.06 mm and 303.5 mm. He suspected that the reason might have been the filtering following the IM.

Estimation was more reliable in unthinned plots than in thinned plots (III). The reason is partly the same as with image overlap: the canopy gaps caused by thinning make the homologous image patches to have different appearances. Another reason for poorer performance in thinned stands may be that there is no texture in dark shadows and, thus, no interest points either.

Whereas the above-mentioned results were logical and in line with previous research, results considering the effect of location in a stereo model and tree species are more ambiguous. The direction of sunlight was a significant explanator in regression-surface models (III). However, without spruce plots the models are not significant anymore. This implies that direction only has an effect on spruce, which can also be observed visually (Figure 5 in III). However, a larger dataset would be needed to confirm this trend. Estimation was most reliable in pine plots. Bias was highest in birch plots, which is somewhat surprising. Sharp spruce crowns should have been a harder task for IM than the smooth crowns of birches. The weather at the time of photography was windy, which may have caused tree sway in birch plots (Korpela 2004). Subsequently, one should be cautious when interpreting these results. The influence of stand age and site quality on the reliability could not be studied here. However, they most likely have an effect (Næsset 2002).

4.4 Semi-automatic detection of tree tops

Previous studies on tree detection have mainly focused on near-nadir views or assessed the accuracy at the plot rather than the individual tree level. The method for linking candidate positions in images and the trees measured in the field proved to be a feasible tool for research.

The accuracy of the LM method in detecting trees uniquely was low, although, at best, over 90% of the stem volume in a plot was found (IV). The probability of tree detection increased when the relative height of a tree increases. Accordingly, the accuracy was highest in the birch plots where suppressed trees had been cleared. A large portion of visible trees were found in spruce and pine plots, too. In the best cases, high omission error was usually bigger nuisance than commission error. The omission errors varied between 7.4% and 25.5% in the birch plots and between 40.6% and 71.5% in the pine and spruce plots. The commission errors ranged from 1.5% to 24.6% in the birch plots and from 4.6% to 33.3% in the pine and spruce plots.

As expected, the accuracy of the method decreased with an increase in the nadir angle (IV). This is because of radial displacement. Near image edges, trees are seen as elongated which causes too many candidate points to hit one crown, and trees cover each other, which causes some trees to be omitted. Illumination class, i.e. if trees were seen as back-lighted, side-lighted or front-lighted, did not affect accuracy.

An increase in smoothing decreased commission error, but increased omission error (IV). Optimal values for the smoothing parameter varied according to different crown sizes and the tree species. In addition, the visibility of spruce branches in the images had a possible effect. Binarization improved the accuracy only slightly, especially with the best cases. The problem of determining optimal parameter values in practice remained unsolved. One possibility is to find near-optimal values by visual, stand level assessment.

The candidate points were displaced from true tree top positions on an image down the trunk, i.e. away from the nadir and towards the sun (IV). The systematic error was efficiently reduced with the correction model. After correction, the positioning accuracy of the method, in XY, excluding the inaccuracy of the field-data, was about 1.3 m on the ground (IV).

The possibilities to use LM as features in IM are attenuated by two facts. Firstly, considering the small search window (three normalised rows in III), it is possible that wrong trees would be matched. However, compared to the results in III, underestimation could be smaller. Secondly, approximately 30-40% of LM in overlapping image pairs were commission points, thus potential obstacles to successful IM. Nevertheless, the effect of these two matters and a comparison against the IM method tested in III, should be empirically verified.

5 DISCUSSION

5.1 The VISU method

A total of ten test areas (189-1892 ha) represented a wide range of forests. Distributions of stand development classes, forest types and tree species varied considerably. A former inventory in the test areas was carried out 10-15 years before VISU. Naturally, there were differences between the 22 photo-interpreters' skills, too. In all the tests, aerial data comprised of false-colour orthophotographs in a resolution of 0.5 x 0.5 m. The scale of the photography was 1:20000 in the first study and 1:30000 in the sequential studies. The time interval between photography and interpretation varied from zero to two years. Consequently, it is possible to make general conclusions from the results despite subjective interpretation and subjectively collected old inventory data.

In the comparison of Uuttera et al. (2002), VISU was rated as the most suitable inventory method for private forestry. The other methods were automatic interpretation at stand level, automatic interpretation at tree level and automatic interpretation at stand level, based on medium resolution satellite images. The productivity of VISU can be expected to rise after a learning period and because forest use declarations can now be given in electronic form, i.e. as a vector layer in GIS. The accuracy may also rise when more detailed Solmu data is updated instead of TASO data and the interpreters gain more experience. In the tests, the interpreters had only very short training. Three critical aspects for the application of the method can be highlighted: 1) the quality of old inventory data, 2) the quality of aerial photographs, and 3) interpretation of thinnings.

The quality of old inventory data and the structure of growing stock are crucial for the success of updating. In a previous inventory, all taxatorical attributes should have been carefully collected. The accuracy can be qualitatively estimated based on what attributes have been collected and who carried out the inventory. In relation to the structure of the forests, it can be roughly stated that updating is at its best in large, single-layer, mature stands on infertile land and at its worst in small, multi-layer, multi-species, young stands on fertile land.

Aerial photographs should be as fresh and of as high a quality as possible. The longer the time expired after photography until interpretation, the more new cuttings are not visible in the photographs. Clouds and bad mosaicking naturally impede interpretation. The images should be radiometrically enhanced, because purchased images are not necessarily optimal for the interpretation.

The most demanding task in the VISU-method is the interpretation of thinnings, which is closely linked with the age and quality of aerial photographs. Logging roads are normally only visible for 3-4 years, in ten-year-old thinnings the crowns have been intergrown. *A priori* data from known operations and proposed cuttings should be utilised whenever possible, but uncertain stands should be directed to field inventory.

Based on the results of the above-reported tests, FCs decided in 2004 to put the VISU-method into practice. Very tight criteria for a planning area to be inventoried with VISU were set, and the method is only to be used in forest estates, that have not ordered a forest plan (Uuttera 2003).

5.2 Automatic interpretation at the stand level

The accuracy of nonparametric, stand level estimation did not meet the quality criteria adduced in Uuttera et al. (2002). In II, a proper radiometric correction was not done, but it was assumed the channel ratio would correct bidirectional reflectance effects. A reliable correction method would probably increase the estimation accuracy, because spectral features would then be better correlated with stand attributes.

The performance of semivariances as indicator attributes in both tests was weak. Evidently, this stems from radial displacement. In other studies where good results in using texture have been achieved, viewing angles have been narrow (e.g. St-Onge and Cavayas 1995, Lévesque and King 1999, Tuominen and Pekkarinen 2005). Hence, it might be wiser to use only inner parts of aerial photographs and mosaic them to ensure sufficient reference data. In Viippero, the low sun elevation may have been another reason for the poor performance of the spectral and textural features.

The accuracy of *k*MSN estimation depends on the number and quality of indicator and design attributes, the number of nearest neighbours *k*, the size and shape of stands and how well the reference data corresponds to the target stands. In practice, a field-check would be needed to determine the accuracy.

The comparison of proposals may give an overly negative impression of the accuracy. This was illustrated by a test in Mustinmäki, where cutting proposals were derived from stand attributes collected in the Solmu inventory. The timing of thinning was decided based on thinning models and the timing of regeneration based on mean diameter and age (Hyvän metsänhoidon suositukset 2001). These proposals were compared to the subjective proposals that were intended to be implemented during the first five-year period. In the field, only 31 of 225 mature stands were marked for regeneration. A total of 94 stands were dense enough to be thinned, but thinning was subjectively proposed for only 44 stands. Consequently, comparison with subjective proposals was later avoided (Table 4).

5.3 Estimation of mean height through digital photogrammetry

In automatic 2D interpretation schemas, mean height is predicted by using image features. If stereo coverage of aerial photographs is available, prediction of mean height by using IM is possible. This can be done as in III, but because underestimation of mean height by IM is considerable and unavoidable, the bias should be corrected with manual photogrammetrical height measurements or field measurements. In the study of Næsset (2002), the biases ranged from -1.56 m (underestimation) to 0.46 m (overestimation) after the correction. The biases were statistically non-significant in all but one stratum.

A more elegant way would be analogue to the one used when estimating stand attributes with ALS data (see e.g. Means et al. 2000). First, several statistics describing the height distribution of the mass points would be extracted. Second, regression models between field measured mean heights and the statistics would be estimated. Third, the models could be used to predict mean heights in another area.

Although ALS provides estimates that are more accurate than can be obtained with stereo IM, and the correction of bias significantly increases costs, it must be remembered that the costs of ALS are still very high. Without bias correction, the extra costs of IM are reasonable. IM estimates also have other potential applications. E.g., template matching based tree top positioning needs an initial guess for the canopy elevation and depth (Korpela 2004).

5.4 Semi-automatic detection of tree tops

Finding individual tree locations from aerial photographs is motivated by two facts: 1) in the continuous updating of a forest information database, stand attributes need to be estimated after a thinning cutting, and 2) tree top candidates might be useful in IM. An ideal stand for automatic, image-based interpretation at the single tree level would be a young or middle-aged stand that has just been thinned from below and will be thinned at least once more before regeneration cutting. The quality of the growing stock is not disturbed, if the next thinning is delayed and the accuracy demand is not as high as in mature stands (Uuttera et al. 2002). In addition, almost all trees are visible from above as the small trees have been mostly cut (Korpela 2004). In IV, pine and spruce plots did not perhaps represent typical thinned plots, since the amount of undergrowth was considerable.

In birch plots, the results for tree detection were quite good in near-nadir views. However, it is a long way from tree detection to complete stand description and despite the excitement surrounding 2D single tree inventory (e.g. McCrystal 2003), the results in Finnish conditions have been a disappointment (e.g. Anttila and Lehikoinen 2002, Korpela and Tokola 2005). There are certainly targets for which the method is excellently suited, e.g. plantation forests, but heterogeneous forest structure and low sun elevation do not form the best conditions for the application of the method. Nonetheless, if a reliable tree species classifier can be developed, a simple tree map could provide a way, e.g., to locate large, ecologically valuable aspens.

5.5 Conclusions

The applicability of the tested approaches is summed up in Table 7. Although only detection of tree tops was tested in IV, approach 4 implies here the whole inventory based on automatic interpretation at tree level (Figure 1). The acceptability of the accuracy of stand attributes and operation proposals in approaches 1, 2 and 4 is defined in Uuttera et al. (2002). In the study of Uuttera et al. (2002), the accuracy limits were subjectively set, based on the accuracy level of the Solmu field inventory. Thus, it is possible that more automatic, less accurate approaches could be more cost-efficient than, e.g., the Solmu inventory. This could be verified with a cost-plus-loss analysis. On average, the accuracies of approaches 1 and 3, which only dealt with the estimation of mean height, were adequate for forest planning. In all the methods, sporadic large standwise errors and systematic error are likely. Therefore, field measurements are necessary in all approaches to ensure quality and to calibrate estimates. These measurements add to the total costs. On the other hand, present, subjective field inventory should also be systematically controlled with objective measurements.

In approaches 1 and 4, proposals for cuttings and silvicultural work were based on estimates of stand attributes and optimisation. In approach 4, low accuracy in stand attributes reflects upon proposals. In approach 2, the proposals were estimated simultaneously with the stand attributes.

The costs of approaches 1 and 4 are dependent on labour-intensive visual interpretation, whereas approaches 2 and 3 are automatic or semi-automatic. One should be very cautious when interpreting the cost figures in Table 7, because only in approach 1 has time consuption been measured. In other approaches, a working cost of 40 €/h was assumed. In approach 2, the time consumption in operative use was estimated within a wide range. The total costs remained low because no extra material costs compared to normal 0.1 €/ha were assumed. In approaches 3 and 4, the extra costs due to more accurate orientation, larger scale and coverage were estimated to be 1.4 €/ha. As in approach 2, in approach 3 the variation in time consumption was also estimated to be large. The total costs are, however, mainly due to material costs. In approach 4, it was assumed that the needed parameter values for tree detection and segmentation are found iteratively, standwise, and that the productivity would be 10-30 ha/h. Field measurements, other than those that are part of VISU, were not included in any estimate.

At the moment, it seems that continuous updating is also possible in private forests. There are two opposite ways of thinking: 1) A stand should be accurately inventoried before an operation (Ståhl et al. 1994). The advantage of this kind of action is that the timing of operation will be correctly defined. In this case, stand attributes could be updated as in VISU or using remote sensing supplemented with field measurements. 2) A stand should be accurately inventoried after an operation. This way further updating is more reliable. Field measurements can be carried out when monitoring cutting quality or as separate work (Korhonen 2002) until more automatic methods for the estimation of stand attributes during operation have been developed (cf. Stendahl and Dahlin 2002).

However, there could still be a demand for less accurate, inexpensive methods in the latter alternative. Part of the forest owners are active and interested in forest planning and part of them are passive. At present, similar inventories are carried out both in the active and passive estates, although stand attributes from passive estates are chiefly required for region level statistics and for guiding in silvicultural work. The information needs of passive estates might well be satisfied with inventory methods like VISU (Varjo 2002).

Table 7. Summary of the applicability of the tested approaches (1 = VISU, 2 = Automatic interpretation at stand level, 3 = Estimation of mean height through digital photogrammetry, 4 = Automatic interpretation at tree level) for the regional forest inventory of private forests in Finland. For comparison the Solmu method is also presented.

Approach	Stand attributes acceptable?	Proposals acceptable?	Costs €/ha	Applicability
Solmu	yes	yes	10^1	Current practice
1	yes	cutting	10^0 [a]	For estates that did not order a plan
2	no	no	10^{-2}-10^0 [b]	Not applicable
3	mean height [c]	-	10^0 [d]	As a part of other methods
4	no	no	10^0-10^1 [e]	Not applicable

[a] Productivity 2-4 times higher than in Solmu.
[b] Working costs 0.03-0.6 €/ha.
[c] RMSE 6-16% at plot level, 70% coverage.
[d] Working costs 0.1-0.4 €/ha, extra material costs compared to 1:30000 images 1.4 €/ha.
[e] Working costs 1.3-4 €/ha, extra material costs compared to 1:30000 images 1.4 €/ha.

However, the division into active and passive owners is not straightforward, as a considerable amount of forest plans are ordered after the inventory. The demand for interpretation time in VISU is, after all, so high that it has usually not been considered worth using because the passive owners are not known, for sure. Thus, the operational use of VISU has not been wide. Therefore, further development of approach 2 would be tempting, since the method is highly automatic. If the accuracy could be raised without greatly increasing the costs, the method could provide an inexpensive base level of information which could be supplemented with more accurate inventory for the active owners.

To illustrate the magnitude of possible cost savings by using these approaches, assume the costs presented in Table 7 and that all the estates of passive owners were inventoried with these methods. In 2002, the area inventoried was 1.1 Mha of which nearly 390000 ha was in the estates of passive owners (Tapion vuositilastot 2003). Then the annual cost savings would be 2-3 M€ by using approach 1, ca. 3 M€ by using approach 2 and 1-2 M€ by using approach 4. The actual savings would, however, be smaller because of missing old inventory data and obligatory field-visits due to operation proposals and calibration.

At present, the most promising remote sensing methods for obtaining accurate stand attribute estimates for active forest estates rely on the measurement of 3D information. In 2D approaches, dbh and volume are derived from dimensions of crown projection, whereas in 3D approaches height can also be utilised. In addition, tree height is correlated more with dbh and volume than dimensions of 2D projection of crown are. With 3D image-based single tree forest inventory, a RMSE of 15% for stand volume can be expected in the best case (Korpela and Tokola 2005). The accuracy of an ALS based inventory is higher, 10-15% (Næsset et al. 2004). The costs of ALS are still very high, but because of small inoptimality losses, ALS based inventory may be profitable (Eid et al. 2004).

Aerial photographs in the context of updating stand level information on growing stock are, at the moment, most useful and operational applications exist for manual or semi-automatic delineation of segments or stands, visual change detection, and tree species identification, especially when used together with ALS.

5.6 Future research needs

There are various issues related to the tested methods that should be clarified. One of the most important is the cost-efficiency of the methods. As far as VISU is concerned, a reasonable time frame for updating should be defined. To help detect thinnings, the use of stereoscopic interpretation and multi-temporal images should be tested.

For automatic 2D interpretation methods, the difficult problem of radiometric correction needs to be solved. In stand level interpretation, the use of only near-nadir image parts or high resolution satellite images should be studied to better utilise textural indicator attributes.

The accuracy of estimating mean height through digital photogrammetry and semi-automatic detection of tree tops should be studied using aerial photographs at a smaller scale. In III and IV, aerial photographs at the scale of 1:12000 were used. Compared to the normal scale of 1:30000, approximately a six fold number of images is needed. Moreover, the change of image overlap from 60 to 70% increases the amount of images by another 30%. Because better results in IM were achieved using the coverage of 70% than that of 60%, a still higher coverage or normal-angle cameras should be tested. Even a coverage of 90% should not be a problem for new digital cameras (cf. Petrie 2003). The usefulness of LM as features in IM could not be determined (IV). For this reason, an application utilising LM as a feature-detector should be realised.

The use of photogrammetrical mean height estimates as auxiliary information when estimating tree or stand attributes in a 2D image domain as well as in a 3D object domain, in segmenting aerial images, in windthrow modeling and in change detection should be explored. This method also has a clear advantage over ALS in one respect: historical photographs enable the examination of forest dynamics over time, if terrain topography is assumed unchanged (St-Onge and Véga 2003, St-Onge et al. 2004).

It is obvious that aerial photographs will continue to be used in stratification or stand delineation in the future. However, because manual delineation is vague and error-prone, the use of (semi-)automatic segmentation should be further studied. In addition, as mentioned above, mean height information could be used in segmentation as an extra channel.

In continuous updating, change detection is not yet fully utilised, mainly because slighter changes have not been reliably found. However, with a time span of 3 to 4 years, these are still visible on bi-temporal aerial photographs. The differences in phenology, illumination conditions and viewing angle should be minimised, i.e. the photographs should be as close to each other as possible with respect to time, date and location (Hyppänen 1999).

Combining information from ALS and high resolution optical images offers synergy (Leckie et al. 2003a), and this is evidently one of the mainstreams in remote sensing based forest inventory research. ALS provides height information, whereas tree species can be inferred using, e.g., aerial photographs. This is why species recognition studies need attention. Another current trend is the gradual substitution of analogue photography with digital photography. The use of digital aerial photographs certainly offers advantages over analogue photography, but their introduction calls for testing.

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