Airborne laser scanning based stand level management inventory in Finland

Maltamo, M.,[1] Packalén, P.,[1] Kallio, E.,[1] Kangas, J.,[2] Uuttera, J.,[3] and Heikkilä, J.[4]

[1] University of Eastern Finland, School of Forest Sciences, matti.maltamo@uef.fi, petteri.packalen@uef.fi, eveliina.kallio@uef.fi
[2] Metsähallitus, jyrki.kangas@metsa.fi
[3] UPM Kymmene Oyj, janne.uuttera@upm-kymmene.com
[3] Forestry Development Centre TAPIO, juho.heikkila@tapio.fi

Abstract

In Finland, a new ALS based stand level management inventory was developed during last few years. The system is based on area based approach of ALS data. Additionally, the spectral and texture features of the aerial images are utilized in order to improve the separation of the tree species. The species-specific stand attributes are simultaneously estimated with a nearest neighbour imputation. The new airborne laser scanning based stand level management inventory system has been successful. During just a few years almost all actors of practical forestry have modified their inventory and planning systems to be compatible with the new inventory procedure which will cover almost 3 000 000 hectares in 2011. This paper describes the background, development and practical application of this inventory system.

Keywords: area based approach, nearest neighbor imputation, operational inventory, species-specific stand attributes

1. Background

In Finland two main forest inventories are sampling based National Forest Inventory (NFI) for large-scale and inventory by compartments for stand level management. When NFI data are combined with remote sensing data and other auxiliary information in multi-source NFI, reliable estimates for small areas can also be obtained (Tomppo 2006). However, the areas considered in multi-source NFI are still considerably larger than one stand and also the information needs of stand level management inventory are different. From the perspective of practical forestry the accuracy requirement for the stand level inventory is about 15–30% RMSE in stand volume (Uuttera *et al*. 2002).

Traditionally, the information for stand level management has been collected with a stand-wise field inventory method, that is, inventory by compartments, in which species-specific forest characteristics are estimated using subjective angle count sampling and partly visual assessment (e.g. Koivuniemi and Korhonen, 2006). This method includes stand delineation from aerial photographs, field visits to each stand, and calculation of stand attributes of interest, mainly volume by tree species and timber assortments. The stand characteristics assessed in the field include age, basal area, mean diameter, and height. These data are used in forest planning, for example, to determine the need for silvicultural operations. In practical forestry the data acquisition costs are about 10 euro per hectare and the costs of the whole forest planning process are over 20 euro. However, in private forestry this process is highly subsidized by the state, which pays about 70% of the cost. Annually this method has been applied to over 1 000 000 million hectares of private forests and additionally also to considerable areas of state and forest company forests.

Inventory by compartments has been applied since the 1950s, which means that practically the whole country has been inventoried several times. During the last decades the development of this inventory system was related to field measurements and calculation routines (e.g. Kilkki and Päivinen 1986; Kangas *et al*. 2004). During the last 15 years there has, however, been strong emphasis on modernizing this method completely. The main reasons for this development are the high costs, subjectivity, and inaccuracy of the basic method. In the 1990s there was already a lot of research concerning the development of this method towards remote sensing applications (e.g. Päivinen *et al*. 1993; Varjo 2002). However the accuracy demands and usability for operational purposes were not fulfilled by different optical imageries. Usually, the RMSE of the stand level RMSE of total volume exceeded 30% (Hyyppä *et al.* 2000; Uuttera *et al.* 2006). It was also difficult to separate tree species and the heterogeneity between images was an issue.

The situation concerning the usability of remote sensing data changed when airborne laser scanning (ALS) data became available. For example in Norway the first studies already showed the accuracy and indicated the usability of these data in the operational stage (Næsset 1997; 2004) The method developed in Norway is based on the variables calculated from the height value distribution of the low pulse density ALS data over a certain area and is, therefore, called an area based approach (or canopy height distribution approach) (see Næsset 2004). In Finland the application of ALS data began with the single tree detection approach, where individual trees were recognized from the canopy height model constructed from high pulse density ALS data (Hyyppä and Inkinen 1999). The accuracy of this approach was also already promising in the first studies (Hyyppä and Inkinen 1999; Maltamo *et al.* 2004) but high data acquisition costs, a lack of algorithms to detect tree species, and considerable threat of bias of tree and stand attribute estimates restricted the development of this method towards the operational stage.

2. Airborne laser scanning based stand level management inventory system of Finland

2.1 System description

Correspondingly, as in other Nordic countries (Næsset 2002; Holmgren 2004) and later in many other countries (Hudak *et al.* 2006; Jensen *et al.* 2006; Hollaus *et al.* 2007; Rombauts *et al*. 2008; Latifi *et al.* 2010), the area based approach was also tested experimentally in Finland starting in 2004 (Suvanto *et al.* 2005; Maltamo *et al*. 2006). The accuracy obtained for stand total volume was superior compared to earlier studies based on either field measurements (Haara and Korhonen 2004) or other remote sensing data (see e.g. Uuttera *et al.* 2006). However, the requirement for estimated species-specific stand attributes was not fulfilled by this approach either.

To overcome the tree species problem, Packalén and Maltamo (2006; 2007; 2008) combined ALS data with aerial images. As in the other applications, here also the independent variables of the system are those calculated from the height and the density distributions of the low-resolution (pulse density < 1 pulse·m^{-2}) ALS data. Additionally, the spectral statistics and the texture metrics of the aerial images are utilized in order to improve the separation of the tree species. The fusion of ALS data and aerial images was further developed in Packalén *et al.* (2009) in order to improve the accuracy of species-specific predictions. The dependent variables of the system are the most essential stand sum and mean attributes, namely volume, basal area, number of stems, mean diameter, and mean height estimated separately for Scots pine, Norway spruce, and tree species group deciduous species.

Since the modelling phase is multivariate the stand attributes are simultaneously estimated with a nearest neighbour (NN) imputation (see Packalén and Maltamo 2007). However, other modelling alternatives such as the Bayesian approach are also possible (Junttila *et al.* 2008). The obtained results have indicated highly accurate results for the stand totals and also for main tree species whereas the accuracy is worse for minor tree species. The chosen non-parametric approach also allows the estimation of species-specific diameter distributions which are compatible with stand attribute estimates (Packalén and Maltamo 2008). These diameter distribution estimates are based on tree diameter measurements of reference plots and, thus, describe the local variability. Alternatively, it is also possible to predict parameters of some theoretical diameter distribution models by using ALS data or to utilize predicted stand attributes and existing parameter models of theoretical diameter distribution models.

Accurate and georeferenced reference plot measurements are a keystone in the new stand level management inventory method (see e.g. Gobakken and Næsset 2009). Georeferencing enables the extraction of the aerial data from exactly the same point as where the field measurements were carried out. For now the number of field reference plots is about 500 plots within the area of each inventory campaign. The ALS based inventory concerns young, maturing, and mature forests but basically seedling stands have been out of the scope so far. The reference plot measurements should represent the existing variation within the inventory area. For the NN method, the limitation is that it is impossible to use it for extrapolation purposes: if the data are not representative, the lowest values of any distribution will be overestimated, while the highest estimates will be underestimated. The multivariate modelling task makes this even more complex since some of the attributes estimated are rare. To capture the true variation within the forest area, the placement of the reference plot measurements should be considered carefully. Usually, the field plot data are not a probability sample in Finland.

When applying the constructed model the stand attributes are estimated by means of plot level reference measurements and aerial data metrics in a wall-to-wall manner. The independent variables are calculated for the field reference plots and for the cells of a 16 m × 16 m grid, which is laid over the inventory area. The cells of the grid are used as estimation units, for which the forest characteristics are imputed from the reference plots by means of aerial data. The use of a grid is corresponds with the Norwegian application (Næsset 2004) and more or less similar systematic approaches have been proposed for remote sensing applications in general for stand level inventories (e.g. Poso 1994). Stand level estimates are aggregated from the grid cells that fall inside the boundaries of each stand. Instead of using grids, micro-stands may be applied as well (e.g. van Aardt *et al.* 2006). The reasoning behind the use of micro-stands is that they divide the area into homogenous parts where the prediction of stand attributes may be more reliable. ALS data also provide excellent possibilities for segmentation.

2.2 Practical arrangements

Since scientific studies have shown that the species-specific estimation accuracy obtained with the ALS based inventory is comparable with the traditional field inventory method (Haara and Korhonen 2004; Maltamo *et al.* 2009; Packalén and Maltamo 2007), the actors in the Finnish forest sector were willing to adopt the new, accurate, and less fieldwork-intensive inventory procedure in the hope of reduced costs. In the case of private forestry it is assumed that a 60% cost saving would occur when compared to field inventory. The scientific basis for the new system was developed in the projects “The Use of Airborne Laser Scanning in the Estimation of Accurate Forest Resources” and “The Use of Airborne Laser Scanning and Aerial Photographs in the Inventory of Timber Sortiments by Tree Species” funded by TEKES, the National Technology Agency of Finland (Maltamo 2007; Maltamo and Kallio 2011). The practical forestry organizations were also involved in these projects.

The change from the old system to the new one was surprisingly fast. In Finland there is no similar tradition of using remote sensing data in stand level inventory as in other Nordic countries. In Finland the use of remote sensing data was earlier restricted to visual stand delineation. Usually there is also a conservative attitude towards changes but in this case the reason for the rapid movement might be twofold. Firstly, there was already a long history of finding new remote sensing based solutions, but suitable data were not found. Secondly, there was a close co-operation between researchers and actors of practical forestry when this system was developed.

In practical applications the ALS and aerial data acquisition, processing of the raw ALS data and aerial images into the independent variables, stand attribute modelling, and calculation of inventory results are done by service providers but the process differs between organizations. In the following the practices of three different organizations are presented.

The forest company UPM Kymmene Oyj started its pilot projects in 2004 and the first fully operational project was in 2008. Currently about half of its 900 000 hectares forest area in Finland has been inventoried by using an ALS application. In UPM Kymmene Oyj micro-stands are applied since their usability is better when planning silvicultural operations. Typically, service providers also collect field reference data as part of the campaign. The situation is almost similar in the state forests managed by Metsähallitus. ALS based forest inventory is already in the operational stage in forest planning systems. So far, about 1 200 000 hectares have been inventoried. There are also other purposes for the data, such as planning the cutting of the marked stands and the need for ditch cleaning.

In the case of private forestry the plan is that the total area to be inventoried with the new method in Finland is about 1.5 million hectares per year, which means that all the private forests will be inventoried during less than one decade. In the case of privately owned forests, the estimated stand level forest characteristics are often further processed to holding-specific forest plans and treatment schedules. The results of the inventory are also used for guidance of forest owners (so-called *Metsaan.fi*). Until now, the regional Forestry Centres, of which there are 13 altogether, have been the major institution that offers forest planning services to the private forest owners. After some pilot studies conducted during the last five years the first practical forest inventories in privately owned forests with the new inventory method were done in 2010 when local Forestry Centres organized bidding in order to conduct inventory of certain areas.

The difference between other organizations and private forestry is that these centres measure the reference plot sample in the privately owned forests with the new inventory method. The reference measurements are carried out independently within the area of each regional Forestry Centre and the intention is that each centre would measure about 500–800 circular sample plots from the mature forests in their inventory area. A set of sample plots is also measured from the sapling and seedling stands. The forest planning experts who previously assessed stand level forest characteristics by means of angle count sampling now measure accurate information on georeferenced sample plots. They also concentrate more on planning, guidance, and service for forest owners. Besides the reference plot measurements, fieldwork is still needed for checking the treatment proposals for seedlings that cannot be estimated accurately enough with the new method. There is also a need for some forest classification information (site class, soil class, etc.) on age and biodiversity issues where information must be taken from old inventory data or must be field checked.

The sample plot placement carried out by the Forestry Centres attempts to mimic the NFI with varying cluster and shorter plot distances, stratification, and subjectively allocated additional measurements. The stratification is performed on the basis of the old inventory data on the forest characteristics and the locations of different stands within the inventory area. The strata are forest site type, dominating tree species, basal area, and mean diameter. This design aims to obtain a good non-probability sample of the forests of the inventory area that includes the true variations and also the extremes of all the variable distributions.

2.3. Specific features

Besides the basic work of the development of the new inventory system many other issues have been tested experimentally as well. Since the NFI also provides a systematic network of field plots, the question of whether this data would also be utilized in stand level management inventory was studied (Maltamo *et al.* 2009). Concerning NFI plots it must be remembered that the plots are angle count plots, which means that 100% coverage with remote sensing data is impossible. According to the results by Maltamo *et al.* (2009) the effect of using angle count samples on accuracy is, however, minor but the current georeferencing of the plots is not adequate and also the sampling design is not optimal for the stand level inventory purposes.

The National Land Survey of Finland is using ALS data for national DTM production (Ahokas *et al.* 2008). The technical requirements for the ALS data in national terrain modelling are almost identical to the requirements of forestry applications but in terrain modelling the primary aim is to acquire leaf-off data. However, using the same (leaf-off) data in national terrain modelling and forestry applications would mean significant cost savings in both campaigns. The usability of leaf-off ALS data in stand level forest inventory was examined by Villikka (2010). The overall conclusion was that leaf-off ALS data are suitable for area based forest inventory in which deciduous and coniferous trees need to be separated. However, the narrow time window when leaf-off ALS data can be collected may restrict the applicability. Correspondingly, in DTM production the laser scanner used may change during one campaign, but this is a critical point for forestry applications (Næsset 2009). In general the results of Villikka (2010) were better with leaf-off than leaf-on data. In addition, leaf-off ALS data per se had the ability to discriminate between deciduous and coniferous trees, which may decrease the inventory costs if the acquisition of aerial images is therefore avoided entirely and if there is a possibility of joint ALS data acquisition between forestry and land survey organizations. Nowadays leaf-off data are already widely applied in private forestry data acquisition in Finland. Altogether about 1 000 000 hectares will be inventoried by leaf-off data in 2011.

One specific feature is also young sapling stands, which usually cover about 25% of the inventory area. Considerable savings of the costs of field checks which are currently a bottleneck in the system could be avoided if at least part of these stands could be covered by ALS inventory. The information needs of these stands differ. Instead of species-specific stand attributes it is more important to know the timing of the next silvicultural treatment. The developed ALS based inventory as such will not provide such information although it can be expanded to cover seedlings as well. There have been some efforts to predict characteristics of young stands or alternatively the need for treatments (Næsset and Bjerknes 2001; Korpela *et al.* 2008; Närhi *et al.* 2008). Research concerning the inclusion of seedling stands as a part of ALS based stand level inventory is currently going on in Finland.

One important issue is the bioenergy content of forests. Like volume, biomass can also be predicted by using ALS. If the ALS based characterization of a stand is at tree level, biomass components (stem, branches, stump) can also be calculated (Kotamaa *et al.* 2010). It is also possible to find stands with the possibility of bioenergy cutting or other silvicultural thinning and to characterize the amount of removed biomass or logging residues in thinnings (Kotamaa *et al.* 2010; Pyörälä 2010; Räsänen 2010; Vastaranta *et al.* 2011).

3. The future

The new airborne laser scanning based stand level management inventory system has been successful in Finland. During just a few years almost all actors of practical forestry have modified their inventory and planning systems to work with ALS data and the inventory will cover almost 3 000 000 hectares in 2011. Nowadays the area based approach is applied but due to the use of diameter distribution models the characterization of tree stock can be transformed to tree level. Although this inventory system is still quite new there is already a lot of research work related to the development of this system or completely new systems.

In relation to the current system, the most serious drawback is still the separation of tree species. Although the main tree species can usually be described, the error in the case of minor tree species can still be very high. If the estimated main tree species of a stand is wrong this is a severe error for a holding-specific forest plan. Development related to this issue might be related to improved algorithms or other data sources such as hyperspectral data, whose operational use is, however, still questionable. Other big issues are the characterization of multilayered and seedling stands as well as information on biodiversity aspects and site classes.

The operational application of ALS data also still has many bottlenecks which are not directly related to the ALS technique. For example, co-operation between different organizations (e.g. ALS raw data processing and field measurements), rapid changes in established practices in organizations, restrictions of information systems, different local conditions in different parts of the country, and weather conditions for optical image acquisition cause difficulties in operational use. For example, the linkage of estimated stand attributes or diameter distributions and forest planning systems might need some improvement.

If the whole inventory approach is changed in the near future one question might be whether single tree detection would be applicable for operational purposes. During the last five years the prices of ALS data have gone down and there has been development of the algorithms to predict tree species and stand attributes (e.g. Korpela *et al.* 2010; Vauhkonen *et al*. 2010). As a result of this development the differences in accuracy between these two approaches have more or less vanished (e.g. Packalén *et al.* 2008; Vastaranta *et al.* 2009; Peuhkurinen *et al.* 2011). One interesting alternative is the so-called semi-individual tree crown approach (Breidenbach *et al.* 2010), where segments including zero, one, or several trees are imputed with non-parametric methods, thus avoiding bias in the resulting stand level estimates.

If the possible change from an area based approach to single tree detection is discussed there are different views. Changing the inventory system from one remote sensing system to another might be easier now since the first remote sensing based inventory system is now in operational use. On the other hand, if no considerable improvement in the description of tree stock or in the accuracy were to be achieved, the change might be needless from an operational point of a view. There might also be some new difficulties related to information systems. Additionally, although single tree detection can, in principle, characterize each tree it is common for certain trees or tree groups not to be observed. This might happen especially in clustered stands where this kind of information is crucial from the silvicultural point of view, and if this information is not obtained the benefit of single tree detection is lost.

The development of inventory systems is, of course, not only related to the choice between area based and single tree detection approaches. There are different types of ALS data, such as full waveform data, and even different platforms. Their usability in different types of inventory varies and in the case of stand level management inventory these issues are still an open question. It should also be remembered that to be applicable in practice their operational use should cover very large areas annually.

References

Ahokas, E., Kaartinen, H., and Hyyppä, J., 2008. On the quality checking of the airborne laser scanning-based nationwide elevation model in Finland. 21st ISPRS Congress Beijing 2008. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 37(B1/I), 267–270.

Breidenbach, J., Næsset, E., Lien, V., Gobakken, T., and Solberg, S., 2010. Prediction of species specific forest inventory attributes using a nonparametric semi-individual tree crown approach based on fused airborne laser scanning and multispectral data. *Remote Sensing of Environment*, 114 (4), 911–924.

Gobakken, T. and Næsset, E., 2009. Assessing effects of positioning errors and sample plot size on biophysical stand properties derived from airborne laser scanner data. *Canadian Journal of Forest Research*, 39 (5), 1036–1052.

Haara, A. and Korhonen, K.T., 2004. Kuvioittaisen arvioinnin luotettavuus. *Metsätieteen aikakauskirja*, 4/2004, 489–508. (In Finnish.)

Hollaus M., Wagner W., Maier B., and Schadauer K., 2007. Airborne laser scanning of forest stem volume in a mountainous environment. *Sensors*, 7, 1559–1577.

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

Hudak, A.T., Crookston, N.L., Evans, J.S., Falkowski, M.J., Smith, A.M.S., Gessler, P.E., and Morgan, P., 2006. Regression modeling and mapping of coniferous forest basal area and tree density from discrete-return lidar and multispectral satellite data. *Canadian Journal of Remote Sensing*, 32, 126–138.

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

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

Jensen, J.L.R, Humes, K.S., Conner, T., Williams, C.J., and DeGroot, J., 2006. Estimation of biophysical characteristics for highly variable mixed-conifer stands using small-footprint lidar. *Canadian Journal of Forest Research*, 36, 1129–1138.

Junttila, V., Maltamo, M., and Kauranne, T., 2008. Sparse Bayesian estimation of forest stand characteristics from ALS. *Forest Science*, 54, 543–552.

Kangas A., Heikkinen E., and Maltamo M., 2004 Accuracy of partially visually assessed stand characteristics – A case study of Finnish forest inventory by compartments. *Canadian Journal of Forest Research*, 34, 916–930.

Kilkki, P. and Päivinen, R., 1986. Weibull function in the estimation of the basal area DBH-distribution. *Silva Fennica*, 20, 149–156.

Koivuniemi, J. and Korhonen, K.T., 2006. Inventory by compartments. In: A. Kangas and M. Maltamo (Eds.). *Forest Inventory. Methodology and Applications. Managing Forest Ecosystems.* Vol. 10. Springer, Dordrecht: 271–278.

Korpela I., Tuomola T., Tokola T., and Dahlin B., 2008. Appraisal of seedling-stand vegetation with airborne imagery and discrete-return LiDAR – an exploratory analysis. *Silva Fennica,* 42 (5), 753–772.

Korpela, I., Ørka, H.-O., Maltamo, M., Tokola, T., and Hyyppä, J., 2010. Tree species classification in airborne LiDAR data: influence of stand and tree factors, intensity normalization and sensor type. *Silva Fennica,* 44, 319–339

Kotamaa, E., Tokola, T., Maltamo, M., Packalén, P., Kurttila, M., and Mäkinen, A., 2010. Integration of remote sensing-based bioenergy inventory data and optimal bucking for stand-level decision making. *European Journal of Forest Research*, 129, 875–886.

Latifi, H., Nothdurft, A., and Koch, B., 2010. Non-parametric prediction and mapping of standing timber volume and biomass in a temperate forest: application of multiple optical/LiDAR-derived predictors. *Forestry,* 83 (4), 395–407.

Maltamo, M., 2007. *Laserkeilauksen käyttö metsävarojen tarkassa inventoinnissa (METSÄLASER).* Loppuraportti. 15 p. (In Finnish.)

Maltamo, M. and Kallio, E., 2011. *Laserkeilauksen ja ilmakuvien käyttö metsävarojen puu- ja puutavaralajeittaisessa inventoinnissa (METSÄLASER2).* Loppuraportti. 21 p. (In Finnish.)

Maltamo, M., Eerikäinen, K., Pitkänen J., Hyyppä, J., and Vehmas, M., 2004. Estimation of timber volume and stem density based on scanning laser altimetry and expected tree size distribution functions. *Remote Sensing of Environment,* 90, 319–330.

Maltamo, M., Eerikäinen, K., Packalén, P., and Hyyppä, J., 2006. Estimation of stem volume using laser scanning based canopy height metrics. *Forestry,* 79, 217–229.

Maltamo, M., Packalén, P., Suvanto, A., Korhonen, K.T., Mehtätalo, L., and Hyvönen, P., 2009. Combining ALS and NFI training data for forest management planning – a case study in Kuortane, Western Finland. *European Journal of Forest Research,* 128, 305–317.

Næsset, E., 1997. Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sensing of Environment,* 51, 246–253.

Næsset, E., 2002. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. *Remote Sensing of Environment,* 80, 88–99.

Næsset, E., 2004. Practical large-scale forest stand inventory using a small airborne scanning laser. *Scandinavian Journal of Forest Research,* 19, 164–179.

Næsset, E., 2009. Effects of different sensors, flying altitudes, and pulse repetition frequencies on forest canopy metrics and biophysical stand properties derived from small-footprint airborne laser data. *Remote Sensing of Environment*, 113, 148–159

Næsset, E. and 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, 328–340.

Närhi, M. Maltamo, M, Packalén, P., Peltola, H., and Soimasuo, J., 2008. Kuusen taimikoiden inventointi ja taimikonhoidon kiireellisyyden määrittäminen laserkeilauksen ja metsäsuunnitelmatietojen avulla. *Metsätieteen aikakauskirja,* 1/2008, 5–15. (In Finnish.)

Packalén, P. and Maltamo, M., 2006. Predicting the volume by tree species using airborne laser scanning and aerial photographs. *Forest Science,* 52, 611–622.

Packalén, P. and Maltamo, M., 2007. The k-MSN method in the prediction of species specific stand attributes using airborne laser scanning and aerial photographs. *Remote Sensing of Environment,* 109, 328–341.

Packalén, P. and Maltamo, M., 2008. The estimation of species-specific diameter distributions using airborne laser scanning and aerial photographs. *Canadian Journal of Forest Research,* 38, 1750–1760.

Packalén, P., Pitkänen, J., and Maltamo, M., 2008. Comparison of individual tree detection and canopy height distribution approaches: a case study in Finland. In: R. Hill, J. Rosette, and J. Suárez (Eds.), *Proceedings of SilviLaser 2008, 8th International Conference on LiDAR Applications in Forest Assessment and Inventory,* 17–19 September 2008. Heriot-Watt University, Edinburgh, UK: 22–29.

Packalén, P., Suvanto, A., and Maltamo, M., 2009. A two stage method to estimate species-specific growing stock by combining ALS data and aerial photographs of known orientation parameters. *Photogrammetric Engineering & Remote Sensing*, 75, 1451–1460.

Päivinen, R., Pussinen, R., and Tomppo, E., 1993. Assessment of boreal forest stands using field assessment and remote sensing. In: *Operalization of Remote Sensing. Proceedings of Earsel 1993 Conference*, 19–23 April 1993. ITC Enshedene, the Netherlands. 8 p.

Peuhkurinen, J., Mehtätalo, L., and Maltamo, M., 2011. Comparing ALS based individual tree and area based methods in forest inventory. *Canadian Journal of Forest Research,* 41, 583–598.

Poso, S., 1994. Metsätalouden suunnittelu uusiin puihin. Voidaanko silmävaraisesta kuvioittaisesta arvioinnista luopua? *Metsätieteen aikakauskirja,* 1/1994.

Pyörälä, P., 2010. *Bioenergiakohteiden tunnistaminen laserkeilauksella*. University of Eastern Finland, Faculty of Science and Forestry, candidate´s thesis. 20 p. (In Finnish.)

Räsänen, I., 2010. *Puuston ensiharvennustarpeen ja tilajärjestyksen määrittäminen laserkeilauksella*. University of Eastern Finland, Faculty of Science and Forestry, master´s thesis. 58 p. (In Finnish.)

Rombouts, J., Ferguson, I.S., and Leech, J.W., 2008. Variability of LiDAR volume prediction models for productivity assessment of radiata pine plantations in South Australia. In: R. Hill, J. Rosette, and J. Suárez (Eds.), *Proceedings of SilviLaser 2008, 8th International Conference on LiDAR Applications in Forest Assessment and Inventory,* 17–19 September 2008. Heriot-Watt University, Edinburgh, UK: 39–49.

Suvanto, A., Maltamo, M., Packalén, P., and Kangas, J., 2005. Kuviokohtaisten puustotunnusten ennustaminen laserkeilauksella. *Metsätieteen aikakauskirja,* 4/2005, 413–428. (In Finnish.)

Tomppo, E., 2006. The Finnish multi-source National Forest Inventory – small area estimation and map production. In: A. Kangas and M. Maltamo (Eds.). *Forest Inventory. Methodology and Applications. Managing Forest Ecosystems.* Vol. 10, Springer, Dordrecht: 195–224.

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

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

van Aardt, J.A.N., Wynne, R.H., and Oberwald, R.G., 2006. Forest volume and biomass estimation using small-footprint lidar-distributional parameters on a per-segment basis. *Forest Science*, 52, 636–649.

Varjo, J., 2002. Metsäsuunnittelun tietohuollon järjestäminen tulevaisuudessa. *Metsätieteen aikakauskirja*, 3/2002, 537–540. (In Finnish.)

Vastaranta, M., Holopainen, M., Haapanen, R., Yu, X., Melkas, T., Hyyppä, J., and Hyyppä, H., 2009. Comparison between an area-based and individual tree detection method for low-pulse density ALS-based forest inventory. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(3/W8), 147–151.

Vastaranta, M., Holopainen, M., Yu, X., Hyyppä, J., Hyyppä, H., and Viitala, R., 2011. Predicting stand-thinning maturity from airborne laser scanning data. *Scandinavian Journal of Forest Research,* 26, 187–196.

Vauhkonen, J., Korpela, I., Maltamo, M. and Tokola, T., 2010. Nearest neighbor imputation of tree attributes from airborne laser scanning data. *Remote Sensing of Environment*, 114, 1263–1276.

Villikka, M., 2010. *The Suitability of Leaf-off Airborne Laser Scanner Data for Species Group Level Forest Inventory.* University of Eastern Finland, Faculty of Science and Forestry, master´s thesis in Forest Planning and Economics. 44 p.