ESTIMATION OF TIMBER ASSORTMENTS USING LOW-DENSITY ALS DATA

M. Holopainen [a, *], M. Vastaranta [a], J. Rasinmäki [a], J. Kalliovirta [a], A. Mäkinen [a], R. Haapanen [b], T. Melkas [c], X. Yu [d], J. Hyyppä [d], H. Hyyppä [e]

[a] University of Helsinki, Department of Forest Resource Management, Finland -(markus.holopainen, mikko.vastaranta, jussi.rasinmäki, jouni.kalliovirta, antti.mäkinen)@helsinki.fi
[b] Haapanen Forest Consulting - reija.haapanen@haapanenforestconsulting.fi
[d] Metsäteho Ltd - timo.melkas@metsateho.fi
[c] Finnish Geodetic Institute - (xiaowei.yu, juha.hyyppa)@fgi.fi
[e] Helsinki University of Technology, Research Institute of Modelling and Measuring for the Built Environment, Finland - hannu.hyyppa@tkk.fi

KEY WORDS: Forestry, Inventory, Distributed, Laser scanning, Estimation

ABSTRACT:

The objective here was to analyse the effects of inventory errors on the prediction of assortment outturn volumes carried out in current airborne laser scanning (ALS) inventory method and forest-planning simulation computing in Finland. Harvested logging machine data of 12 clear-cutting stands (5300 trees) in Evo (southern Finland) study area was used as field reference of the study. Prediction error of assortment outturn volumes contains forest inventory, stem distribution generation, prediction of stem form and simulation of bucking errors. ALS inventory-related bias in estimated timber assortments ranged from -5.1 m^3/ha to 20.5 m^3/ha and RMSE from 6.0 m^3/ha to 46.2 m^3/ha. Accuracy of the estimated stem distributions varies in different stands. The results showed that the accuracy of the estimates of timber assortments is considerably poorer than the accuracy of stands mean characteristics.

1. INTRODUCTION

Standwise forest inventory (SWFI) and increasingly ALS inventory data acts as input data in forest management planning calculations. After the inventory, stand development and the effects of silvicultural treatments are simulated, using various models (e.g. Hynynen et al. 2002). In forest management computations, the quality of the input data describing the stand's present state has a decisive impact on the reliability of the output results (Haara 2005). The longer the reference period, the larger the output errors; thus, inaccurate input data are especially problematic in the case of forestry yield value determination throughout the rotation period. In addition, inaccurate input data cause significant nonoptimal losses in forest planning and forest silviculture if the timing of various treatments fails due to erroneous input data (e.g. Eid 2000, Eid et al. 2004, Holopainen and Talvitie 2006, Holopainen et al. 2009).

Airborne laser scanning (ALS) is the most accurate remote-sensing technique for standwise forest inventory providing accuracies (RMSEs) ranging between 10% and 27% for the mean volume at stand or plot level (e.g. Næsset 1997, 2002, Holmgren 2003, Lim et al. 2003, Packalén and Maltamo 2006, Holopainen et al. 2008). For comparison, the mean errors of traditional standwise field inventory (SWFI) used in operational forest management planning vary for mean volume from 16% to 38% in Finland (Poso 1983, Haara and Korhonen 2004, Saari and Kangas 2005). Current ALS data acquisition costs are comparable to those of SWFI. The two main approaches to deriving forest information from small-footprint ALS data have been those based on laser canopy height distribution (area-based method, Næsset 1997, 2002) and individual tree detection (Hyyppä and Inkinen 1999, Persson et al. 2002, Leckie et al. 2003, Popescu et al. 2003, Maltamo et al. 2004).

Acquisition of forest-planning data is currently in a phase of radical change. Several forest organizations in Finland are currently replacing traditional SWFIs with area-level ALS inventories in which low-density (less than two pulses per m^2) ALS data are used as an auxilliary data source. This new forest resource information provides new opportunities for forest management planning and e.g. forest estate valuation but, on the other hand, also sets new demands on forest development models and simulation methodologies. It, for example, offers several alternatives for forming stem distributions.

Area based ALS features can be utilized for the formation of stem diameter distributions in several ways. One alternative is to first estimate the mean stand characteristics and then apply stem distribution models based on theoretical distributions (e.g. the Weibull distribution). Another alternative is to use ALS features to directly estimate stem distribution parameters in a manner proposed and studied by Gobakken & Naesset (2004, 2005), Maltamo et al. (2006), Bollandsås and Naesset (2007) or by Breidenbach et al. (2008). Third possibility is to utilize stem distribution series measured for field plots used as reference in k-NN or k-MSN method (Packalén and Maltamo 2008).

Most of the ALS research in forest inventory has focused on the estimation of mean characteristics, such as plot or stand mean height or mean volume (e.g. Naesset 2002, Maltamo et al. 2006, Holopainen et al. 2008). However, from the standpoint of both forest value assessment and operative timber harvesting, the prediction of species-specific assortment outturn volumes, namely pulp wood and saw wood, is by far the most essential issue. For example, the economic value of a forest stand cannot be accurately determined on the basis of total stem volume only. Instead, information on tree species and the stem distribution is

* Corresponding author

required to reliably determine the distribution of the total stem volume in various assortments.

The significance of tree species-specific estimates in forest-planning simulation and optimization calculations is considerable (e.g. Holopainen et al. 2008). It is thus a great deficit, that the accuracy of tree species-specific estimates is considerably poorer than mean volume estimate. On the level of a forest stand (compartment), which generally is the unit of operations, Packalén and Maltamo (2007) obtained relative tree species-specific RMSEs from 28% (pine) to 62% (deciduous). These results are fully comparable to the traditional SWFI estimation, which is prone to error, as well. Haara and Korhonen (2004) investigated the accuracy of SWFI in eastern Finland. Their study showed that on the stand level the relative RMSE varied from 29% (pine) to 65% (deciduous), while the relative RMSE of stand mean total volume was 25%.

One problem in examination of timber assortment-level estimation accuracy of ALS inventory is that it requires sufficiently accurate ground reference data. In practice, the best method for acquiring such data is to use measuring data gathered by logging machines. However, to utilize these kinds of data as reference data for an ALS inventory, a rather complicated experimental arrangement is required to synchronize logging and imaging time schedules and identify felled trees.

The objective here was to analyse the effects of inventory errors on the prediction of assortment outturn volumes carried out in current ALS inventory method and forest-planning simulation computing in Finland. Harvested logging machine data was used as field reference of the study.

2. METHOD

2.1 Study area

The research material comprised of 12 clear-cut forest stands (Table 1) located in an approximately 2000-ha managed forested area in the vicinity of Evo, Finland (61.19° N, 25.11° E).

The compartments) were spruce-dominant (83%). The delineation of all study compartments was checked using global positioning system (GPS) measurements.

	Age	BA	N	Dg	Hg	Area
Mean	88	18.5	1228	30.5	19.1	1.1
Min	51	12.3	211	22.8	14.4	0.2
Max	123	24.0	9556	37.3	23.6	1.9
Stdev	22	3.1	2771	3.9	3.1	0.6

Table 1. Statistics of age (years), basal area (BA, m^2/ha), stem number (N, 1/ha), mean diameter (Dg, cm), mean height (Hg, m) and area (ha) of the compartments according to the standwise field invetory data.

2.2 Logging machine mensurations

Data obtained by the logging machines were utilized in the study as reference data. The logging machines gathered so called STM data according to the Standard for Forest Data and communication (StanForD 2006). An STM file includes data for each felled tree regarding the logging machine's position at the time of felling, stem diameters at 10-cm intervals from the felling height to the final bucking height, tree species, bucking parameters (e.q price matrix, demand matrix) and bucked timber assortment volumes. Bucked assortment volumes include volumes of saw- (minimum diameter>15 cm) and pulp wood (minimum diameter ≤ 7 cm).

The logging machine information obtained covered 5300 felled trees. An STM file was saved for each felled tree producing commercial timber. STM data were obtained for all trees felled in clear-cutting compartments. Stem distribution series, assortment outturn volumes and mean stock characteristics for each clear-cutting compartment were derived, using stem diameter and length information present in the STM files.

The diameter at breast-height (dbh) was derived as each stem's 12^{th} measured diameter (10-cm stump + 120 cm = 130 cm). Total tree height was estimated, based on the commercial timber height present in the STM file.

2.3 ALS inventory

The ALS data were acquired in midsummer 2006. The flying altitude was 1900 m. The density of the pulses returned within the field plots was 1.8/m^2 (only, first, intermediate or last; 1.3/m^2 if only or first pulses were considered). A digital elevation model (DEM) and consequently heights above ground level were computed by the data provider. Same-date aerial photographs were obtained with a Vexcel Ultracam digital camera, as well. The photographs were orthorectified, resampled to a pixel size of 0.5 m and mosaiced to a single image covering the entire area. The near-infrared (NIR), red (R) and green (G) bands were available.

Modelling field reference data for ALS-inventory were gathered from the study area in midsummer 2007. Treewise field measurements from 264 fixed-radius (10 m) plots were collected and plot level characteristics calculated. There was a 1-year gap between the acquisition of ALS data and field measurements and logging machine measurements; the latest growth was subtracted.

Several statistical and textural features were extracted from the ALS data and aerial photographs. The extraction window was 16 x 16 m, which has been used in operative ALS inventories in Finland. The features included means and standard deviations of spectral values of aerial photographs and ALS height and intensity, Haralick textural features (Haralick et al. 1973; Haralick 1979) derived from spectral values, ALS height and intensity, and standard texture referring to a set of averages and standard deviations of spectral values, ALS height and intensity. The height statistics for the first and last pulses were calculated as in Suvanto et al. (2005): mean and maximum height, standard deviation and coefficient of variation of height, heights at which certain relative amounts of laser points had accumulated as well as percentages of laser points accumulated at various relative heights. Only pulses exceeding a 2-m height limit were included to remove hits to ground vegetation and bushes. Finally, percentages of points under 2-m in height were added. The total number of features in the final dataset was 172. All features were standardized to a mean of 0 and std of 1. ALS-feature selection was based on the genetic algorithm method presented e.g. by Goldberg (1989). A reduced set of features (11 features, see Holopainen et al., 2008) was used in the estimation of stand characteristics.

The estimation method was k-NN, which has long been used in Finnish remote sensing -aided forest inventory applications (e.g. Kilkki and Päivinen 1987; Tokola 1990, Muinonen and Tokola 1990; Tomppo 1991). The nearest neighbours were determined by calculating the Euclidean distances between the observations in the n-dimensional feature space. The number of nearest neighbours was set to 5.

2.4 Determination of stem distributions

Based on mean characteristics obtained by the ALS inventory, stem distribution series were generated for each study compartment. Reference stem distribution series were derived for each compartment, using logging machine STM data. These series are based on the felled trees and do not include generation errors. Generation of stem distribution series was carried out with the SIMO system (Rasinmäki et al. 2009) incorporating the Weibull distribution for 1-cm diameter classes. Separate distribution models were applied for pine (Mykkänen 1986), spruce (Kilkki and Päivinen 1986) and birch (Siipilehto 1999).

2.5 Determination of assortment volumes

The stem form of each diameter class in the generated stem distribution series was predicted, using Laasasenaho's (1982) stem curves. The predicted stem form was then used to determine assortment volumes for each diameter class. Bucking was performed, using Näsberg's (1985) dynamic algorithm.

3. RESULTS

3.1 Accuracy in estimation of mean characteristics

ALS inventory results of basal area (BA), mean diameter (Dg) and mean height (Hg) of clear cut stands were compared to reference data calculated using logging machine STM data. Bias and RMSE values are shown in Table 2. Accuracies of the ALS inventory are at the same level as in previous studies in the same area (e.g. Holopainen et al. 2008).

		BA	Dg	Hg
ALS	Bias	3.5	-2.9	-0.6
ALS	Bias-%	17.8	-10.2	-2.8
ALS	RMSE	4.5	6	2.6
ALS	RMSE-%	22.7	21.2	12.4

Table 2. Accuracy of the ALS-inventory in the logging compartments, BA (m^2/ha), Dg (cm) and Hg (m).

3.2 Accuracy in estimation of timber assortments

Prediction error of assortment outturn volumes contains forest inventory, stem distribution generation, prediction of stem form and simulation of bucking errors. The combined effects of all error sources were examined in this study.

		Saw wood			Pulp wood		
		Pine	Spruce	Birch	Pine	Spruce	Birch
ALS	BIAS	8.9	20.5	-1.8	0.2	-5.1	14.6
ALS	BIAS%	100.8	19.4	-22.2	5.3	-21.1	123.9
ALS	RMSE	19.9	46.2	9.2	6.0	11.5	19.1
ALS	RMSE%	225.0	43.7	116.5	142.5	47.1	161.8

Table 3. Accuracy in estimation of timber assortments based on ALS, m^3/ha

Table 3 shows that ALS inventory-related bias ranged from -5.1 m^3/ha to 20.5 m^3/ha and RMSE from 6.0 m^3/ha to 46.2 m^3/ha. Based on these results, it should be noted that accuracy level ofmean characteristics provided by ALS inventory were not achieved for timber assortments. The great magnitude of the pine- and birch-related relative errors is a consequence of the relatively minor respective logging outturns. A more realistic view of the effect of inventory error on pine and birch assortment volumes can therefore be acquired by examining the absolute accuracy statistics.

3.3 Predicted stem distributions

True stem distribution series were determined by a logging machine (STM). In addition to the true stem distribution series, predicted stem distribution series were formed for each clear-cutting compartment investigated in the study. Predicted series were generated on the basis of mean stock characteristic output by the ALS inventory (ALS). The essential results concerning stem distribution series generation are presented in the stand level figures 1, 2 and 3.

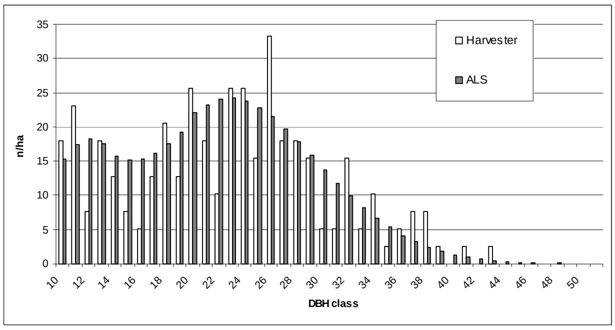

Figure 4. Predicted (ALS) and true stem distributions in a compartment with only slight estimation errors in basal area and mean diameter.

In figure 4, there is a compartment where basal area is overestimated by 1.3 m^2/ha and mean diameter underestimated by 0.8 cm. Still, the theoretical stem distribution does not represent accurately the true stem distribution series which inflicts errors varying from -3.9 m^3/ha to 16.9 m^3/ha in tree species specific saw log volumes and -10.1 m^3/ha to 6.0 m^3/ha to respective pulp wood volumes. Both variables basal area and mean diameter are overestimated, 5.3 m^2/ha and 2.1 cm, respectively, in the stand where stem distributions are presented in figure 5. Predicted stem distribution cannot describe the real variation between diameter classes. Errors in species specific saw log volumes varies from -5.5m^3/ha to 53.0m^3/ha and respective pulp wood volumes from -16.4m^3/ha to 5.3m^3/ha. Extreme-case is presented in figure 6. Mean diameter has been underestimated (5.2 cm) as basal area overestimated (2 m^2/ha). That kind of errors lead to totally biased stem distribution and inaccurate estimation of timber assortments. Errors in species specific saw log volumes varies from -91.0m^3/ha to 47.5m^3/ha and respective pulp wood volumes from -8.3m^3/ha to 27.6m^3/ha.

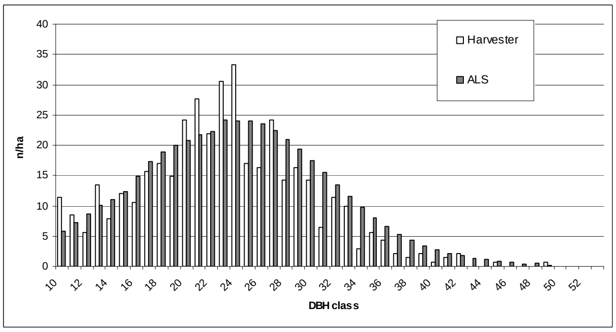

Figure 5. Predicted (ALS) and true stem distributions in a compartment where both basal area and mean diameter are overestimated.

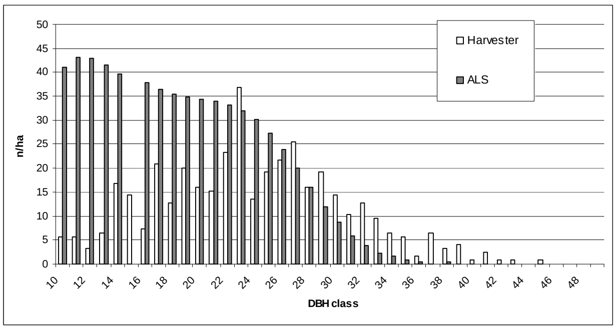

Figure 6. Predicted (ALS) and true stem distributions in a compartment, with overestimated basal area and underestimated mean diameter.

4. DISCUSSION

In the present study we investigated the accuracy of timber assortment volumes predicted by operational low-pulse, area-based, ALS inventory and forest management planning simulation in Finland. Analyses were performed for clear-cuttings, field reference data consisted of a total of 5300 stems felled in 12 logging compartments.

Errors in timber assortment level were higher than errors of clear cut stand's mean characteristics (see Tables 2 and 3). When analysing figures 1-3 it can be seen that quality of ALS-based diameter distribution series has great variance even if mean characteristics are close to true ones.

The most reliable results for the accuracy of the two inventory methods were derived for spruce saw timber and pulpwood assortments, because spruce was clearly the most common tree species in the clear-cutting compartments. In addition, one must take into account the fact that since the study data covered clear-cutting compartments only, the results cannot be generalized to consider all development classes.

Our results concerning the accuracy of low-pulse ALS inventory were slightly poorer than the plot-level ALS results in a study by Peuhkurinen et al. (2008) obtained with a k-NN method using ALS features and aerial photographs. Peuhkurinen et al. (2008) obtained relative RMSEs for spruce saw log volumes of 32.1% and bias of -2.3%, respectively. That accuracy is somewhat comparable with our results of uncertainty caused by ALS inventory in prediction of spruce saw log assortment.

Packalen & Maltamo (2008) tested low-pulse ALS data (0.7 pulses / m2) and spectral and textural features of calibrated aerial photograph in the prediction of species-specific diameter distributions. When they used a similar Weibull distribution method than we did, the accuracies of Scots pine logwood, Norway spruce logwood and deciduous logwood were (bias% in brackets) 40.97% (-3.27%), 61.06% (-25.78%), 142.93% (-37.62%).

In this study we wanted to focus in uncertainty of current forest management planning simulation methods in Finland, i.e. despite promising results of other possibilities to utilize area-level ALS inventory data (Gobacken & Næsset 2004, Maltamo et al. 2006, Packalén & Maltamo 2008), we used mean characteristics and theoretical weibull distribution series in the simulation.

REFERENCES

Bollandsås, O.M., and Næsset, E., 2007. Estimating percentilebased diameter distributions in uneven-sized Norway spruce stands using airborne laser scanner data, *Scand. J. For. Res*. 22, pp. 33–47.

Breidenbach, J., Gläser, C. and Schmidt, M., 2008. Estimation of diameter distributions by means of airborne laser scanner data. *Canadian Journal of Forest Research*, 38, pp. 1611-1620.

Eid, T. 2000. Use of uncertain inventory data in forestry scenario models and consequential incorrect harvest decisions. *Silva Fennica*, 34, pp 89-100.

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

Gobakken, T., and Næsset, E., 2004. Estimation of diameter and basal area distributions in coniferous forest by means of airborne laser scanner data. *Scand. J. For. Res*., 19, pp. 529–542.

Gobakken, T. and Næsset, E., 2005.Weibull and percentile models for lidar-based estimation of basal area distribution. *Scand. J. For. Res*., 20, pp. 490-502.

Goldberg, D. E., 1989. Genetic algorithms in search, optimization, and machine learning. Addison-Wesley Publishing Company, Reading, Massachusetts, 412 p.

Haara, A. and Korhonen, K., 2004. Kuvioittaisen arvioinnin luotettavuus. *Metsätieteen aikakauskirja* 4, pp. 489-508. (in Finnish).

Haara, A., 2005. The uncertainty of forest management planning data in Finnish non-industrial private forestry. Doctoral Thesis. Dissertationes Forestales 8. University of Joensuu 34 p + 5 appendices.

Haralick, R. M., Shanmugan, K. and Dinstein, I., 1973. Textural features for image classification. *IEEE Transactions on Systems, Man and Cybernetics* 3, 6, pp. 610-621.

Haralick, R., 1979. Statistical and structural approaches to texture. *Proceedings of the IEEE 67*, 5, pp. 786-804.

Holmgren, J., 2003. Estimation of forest variables using airborne laser scanning. PhD Thesis. *Acta Universitatis Agriculturae Sueciae, Silvestria* 278, Swedish University of Agricultural Sciences, Umeå, Sweden.

Holopainen, M. and Talvitie, T., 2006. Effects of data acquisition accuracy on timing of stand harvests and expected net present value. Silva Fennica 40, 3, pp. 531-543.

Holopainen, M., Haapanen, R., Tuominen, S. and Viitala, R. 2008. Performance of airborne laser scanning- and aerial photograph-based statistical and textural features in forest variable estimation. In Hill, R., Rossette, J. and Suárez, J. 2008. *Silvilaser 2008 proceedings*, pp. 105-112.

Holopainen, M., Mäkinen, A., Rasinmäki, J., Hyyppä, J., Hyyppä, H., Kaartinen, H., Viitala, R., Vastaranta, M. and Kangas, A., 2009. Effect of tree level airborne laser scanning accuracy on the timing and expected value of harvest decisions. *European Journal of Forest Research*, in press.

Hynynen, J., Ojansuu, R., Hökkä, H., Siipilehto, J., Salminen, H. and Haapala, P., 2002. Models for predicting stand development in MELA System, Finnish Forest Res. Inst. Res. Pap. 835, pp. 1–116.

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

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

Kilkki, P. and Päivinen, R., 1987. Reference sample plots to combine field measurements and satellite data in forest inventory. Department of Forest Mensuration and Management, University of Helsinki. Research notes, 19, pp. 210-215.

Laasasenaho, J., 1982. Taper curve and volume functions for pine, spruce and birch. *Communicationes. Institute Forestalis Fenniae* 108. 74 p.

Leckie, D., Gougeon, F., Hill, D., Quinn, R., Armstrong, L. and Shreenan, R., 2003. Combined high-density lidar and multispectral imagery for individual tree crown analysis. *Can. J. For. Res.* 29, pp. 633–649.

Lim, K., Treitz, P., Wulder, M., St.Onge, B. and Flood, M., 2003. LIDAR remote sensing of forest structure. *Progress in Physical Geography* 27, pp. 88-106.

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 Sens. Environ*. 90, pp. 319–330.

Maltamo, M., Malinen, J., Packalén, P., Suvanto, A. and Kangas, J., 2006. Nonparametric estimation of stem volume using airborne laser scanning, aerial photography, and stand-register data. *Can J For Res* 36, pp. 426-436.

Muinonen, E. and Tokola, T. 1990. An application of remote sensing for communal forest inventory. Proceedings from SNS/IUFRO workshop: The usability of remote sensing for forest inventory and planning, 26-28 February 1990, Umeå, Sweden. Remote Sensing Laboratory, Swedish University of Agricultural Sciences, Report 4, pp. 35-42.

Mykkänen, R., 1986. Weibull-funktion käyttö puuston läpimittajakauman estimoinnissa. M. Sc. thesis. University of Joensuu, Faculty of Forestry. 80 p. (In Finnish).

Næsset, E., 1997. Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sens. Environ*. 61, pp. 246-253.

Naesset, E., 2002. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. *Remote Sens. Environ*. 80, pp. 88-99.

Näsberg, M., 1985. Mathematical programming models for optimal log bucking. Linköping:Department of Mathematics, Linköping University, 1985. Linköping studies in science andtechnology. Dissertation 132. 200 pages.

Packalén, P. and Maltamo, M., 2006. Predicting the plot volume by tree species using airborne laser scanning and aerial photographs. *Forest Science*, 56, pp. 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, pp. 328-341.

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

Persson, Å., Holmgren, J. and Söderman, U., 2002. Detecting and measuring individual trees using an airborne laser scanner. *Photogrammetric Engineering and Remote Sensing* 68, pp. 925-932.

Peuhkurinen, J., Maltamo, M. and Malinen, J., 2008. Estimating species-specific diameter, distributions and saw log recoveries of boreal forests from airborne laser scanning data and aerial photographs: a distribution-based approach. *Silva Fennica*, 42, pp. 625-641.

Popescu, S., Wynne, R., Nelson, R., 2003. Measuring individual tree crown diameter with lidar and assessing its influence on estimating forest volume and biomass. *Canadian Journal of Forest Research* 29, pp. 564–577.

Poso, S., 1983. Basic features of inventory by compartments. *Silva Fennica* 17, pp. 313–349 (in Finnish).

Rasinmäki, J,, Kalliovirta, J, and Mäkinen, A, 2009. SIMO: an adaptable simulation framework for multiscale forest resource data. Comput Electron Agric 66, pp.76-84.

Saari, A. and Kangas, A., 2005. Kuvioittaisen arvioinnin harhan muodostuminen. *Metsätieteen aikakauskirja* 1, 2005, pp. 5-18.

StanForD, 2006. Skogsforsk: Standard for forest data and communications. Available online at www.skogsforsk.se/.

Suvanto, A., Maltamo, M., Packalén, P. and Kangas, J., 2005. Kuviokohtaisten puustotunnusten ennustaminen laserkeilauksella. *Metsätieteen aikakauskirja*, 2005, pp. 413-428.

Tokola, T., 1990. Satelliittikuvan ja VMI-koealatiedon käyttö metsätalousalueen puuston inventoinnissa. Joensuun yliopisto, metsätieteellinen tiedekunta. Lisensiaattitutkimus. 53 p.

Tomppo, E., 1991. Satellite image-based national forest inventory of Finland. *International Archives of Photogrammetry and Remote Sensing*, 28, pp. 419-424.