Effects on Estimation Accuracy of Forest Variables Using Different Pulse Density of Laser Data

Mattias Magnusson, Johan E.S. Fransson, and Johan Holmgren

Abstract: Collection of airborne laser scanner data for forest inventory is becoming a common practice today. To reduce cost when laser data are collected over large areas, the flight altitude or flight speed may be increased, resulting in low pulse density laser data. The effect of using a different pulse density of laser data on estimation accuracy of forest variables was investigated at stand level. Laser data were acquired by the airborne TopEye system at a 1,200-ha forest area located in southern Sweden (58°30′N, 13°40′E). The 70 selected stands were dominated by Norway spruce [*Picea abies* (L.) Karst.] and Scots pine (*Pinus sylvestris* L.) with tree height in the range of 6–28 m (mean 19 m) and stem volume in the range of 30–620 m^3 ha^{-1} (average 286 m^3 ha^{-1}). Regression analysis was used to establish empirical functions at stand level. The pulse density of laser data was reduced from 25,000 to 40 returns ha^{-1}. By reducing the pulse density the root mean square error (RMSE) for the tree height and stem volume estimation increased from 0.7 to 1.8 m and from 13% to 29%, respectively. A substantial decrease in estimation accuracy of tree height and stem volume could be observed at pulse densities $<$80 returns ha^{-1} (corresponding to about 10 m between adjacent laser returns). The rapid increase in RMSE at these pulse densities could be explained by the less accurate classification of ground returns. With access to a high resolution digital elevation model the RMSE for the tree height and stem volume estimation increased from 0.7 to 1.1 m and from 13% to 23%, respectively, as an effect of the reduced pulse density. Even though the pulse density was reduced to several meters between adjacent laser returns, the estimation accuracies were equal to or better than those commonly obtained by using conventional forest inventory methods, e.g., aerial photo interpretation. This finding implies that low pulse density airborne laser scanner data could be cost efficient to use in inventory for estimation of forest variables at stand level. FOR. SCI. 53(6):619–626.

Keywords: lidar, TopEye, forest inventory, tree height, stem volume

THE STARTING POINT in all forest management planning is the current state of the forest. In this context, analog aerial photographs have been extensively used in forest inventories. Methods for aerial photo interpretation have been developed by, e.g., Åge (1985) and Spencer and Hall (1988). In Norway and Sweden forest inventories have frequently been carried out with interpretation of aerial photographs where stands are delineated and forest stand variables are estimated. To improve stand variable estimation and determine stand boundaries, a subsequent subjective field inventory is often performed. Applying the inventory at stand level offers advantages, as the inventory unit then coincides with the basic treatment unit (Jonsson et al. 1993). A stand is characterized of homogeneous tree cover and uniform site conditions, typically about 0.5–20 ha in size. Characteristics at stand level are requested both for strategic planning at property level and for tactical and operational planning of silvicultural treatments. Stem volume is one of the most important forest variables in forest management planning (Walter 1998), in particular for operational planning (Larsson 1994) (e.g., preparing and allocating resources for thinning and final harvest in the forest). Here, stem volume is the trunk volume of trees per area unit (m^3 ha^{-1}) excluding branches and stumps. By using aerial photo interpretation the estimation accuracy of stem volume in terms of standard error is about 15–25% of the average stem volume and about 1–2 m for the mean tree height (Ståhl 1992, Eid and Næsset 1998, Magnusson et al. 2007). However, aerial photo interpretation is based on manual work and relies on the expertise of the personnel involved.

The technique of using an airborne laser for determining forest canopy characteristics was investigated in the 1980s with a profiling system (Nelson et al. 1984). Today, airborne laser scanner data are becoming available for use in forest inventory. In airborne laser scanning, pulsing lasers are combined with a scanning mechanism. The laser measurements are then distributed on the ground through the scan movement and the forward motion of the aircraft. At

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stand level, airborne laser scanning has been used for estimation of forest variables in boreal coniferous forests (e.g., Means et al. 2000, Hyyppä et al. 2001, Næsset 2002, Holmgren 2004). The studies show that the estimation accuracy of forest variables could be improved by using high pulse density laser data (approximately one or more laser measurements per square meter) compared with that using aerial photo interpretation. In Hyyppä et al. (2001), the standard errors for mean tree height and stem volume were estimated to 1.8 m (9.9% of the mean tree height) and 18.5 m^3 ha^{-1} (10.5% of the average stem volume), respectively, with stem volume in the range of 2–335 m^3 ha^{-1}. In a study with stem volumes ranging from 91–415 m^3 ha^{-1}, stands were divided into three strata according to age class and site quality before evaluation (Næsset 2002). The standard deviations of the differences between predicted and ground-truth values of mean tree height and stem volume were found to be 0.6–1.2 m and 18–32 m^3 ha^{-1} (11.4–14.2%), respectively. In Holmgren (2004), laser data were used to predict mean tree height and stem volume, resulting in root mean square errors (RMSEs) of 0.6 m (3%) and 31 m^3 ha^{-1} (11%), respectively (for the best case investigated) with stem volume in the range of 0–600 m^3 ha^{-1}.

In Næsset et al. (2004) it was concluded that although slightly different procedures and instruments can be used, airborne laser scanners using high pulse density and small footprints (about 0.1–4.0 m) are very useful in practical forest inventories over large areas. However, the quality of the forest variable estimates derived from laser data is affected by sensor characteristics (e.g., pulse density, number of pulse returns, flight height, and scan angle) as well as errors due to complexity of the targets (e.g., topography and canopy cover) (Hyyppä et al. 2004).

In practice, high pulse density laser data for forestry applications have been acquired at relatively low flight altitudes, typically between 500 and 1,000 m above ground level (Næsset et al. 2004). As a consequence, the acquisition is associated with a relative high cost for covering large areas. To reduce cost the flight altitude or flight speed may be increased, resulting in low pulse density laser data.

Few studies have examined the effect on the estimation accuracy of forest variables when the pulse density of laser data is reduced (e.g., Holmgren 2004, Yu et al. 2004, Lovell et al. 2005, Maltamo et al. 2006). In Holmgren (2004), small differences in prediction errors for tree height and stem volume estimation were found when the pulse density was reduced from about 4 to 0.1 returns m^{-2}. At plot level, Maltamo et al. (2006) showed that a simulated reduction of laser pulse density from about 13 to 0.1 returns m^{-2} had no effect on the estimation accuracy of stem volume. However, the studies referred to above reduced the laser pulse density relatively modestly. Therefore, it is of interest to investigate the effect on estimation accuracy of forest variables using heavily reduced pulse densities.

The objective of this study was to evaluate the effect on estimation accuracy of forest tree height and stem volume at stand level using different pulse density of laser data. In particular, high pulse density laser data (2.5 laser measurements per square meter) were reduced by allowing a minimum horizontal distance of 1, 2, . . . , 15 m between adjacent laser returns. The hypothesis is that the estimation accuracy of forest variables will decrease with decreasing pulse density.

Materials and Methods

Test Site

The test site, Remningstorp, is located in the south of Sweden (58°30′N, 13°40′E) and covers about 1,200 ha of productive forestland (Figure 1). The dominant tree species are Norway spruce [*Picea abies* (L.) Karst.], Scots pine (*Pinus sylvestris* L.), and birch (*Betula* spp.). The dominant soil type is till with a field layer consisting of different herbs, blueberry (*Vaccinium myrtillus* L.), and narrow-leaved grass [*Deschampsia flexuosa* (L.) Trin.]. In denser old spruce stands the field layer is absent. The ground elevation is moderately varying between 120 and 145 m above sea level.

Field Data

Data for the test site consisted of a digital stand boundary map in vector format and a forest management plan including forest stand variables from subjective field inventory. In total, 340 stands were stratified into the stem volume ranges 0–100, 100–200, . . . , 600–700 m^3 ha^{-1}. For each stratum stands were randomly selected for field inventory (to assure representation of the entire stem volume range) using the criteria of coniferous stem volume >70% and soil type till.

Figure 1. Location of Remningstorp test site.

These criteria were set up to limit the variation of tree species composition and site quality index that according to Næsset et al. (2004) influence the estimation accuracy of forest variables using laser data. Altogether, 70 stands were inventoried in the field according to the routines in the forest management planning package (FMPP) (Jonsson et al. 1993). The FMPP includes an objective and unbiased method for estimation of forest variables such as stem volume, stem diameter, tree height, and tree species composition at stand level from measurements of individual trees. In particular, sample plots with a radius of 10 m were randomly positioned in a stand-unique square grid. On each plot, all trees were calipered at breast height (i.e., 1.3 m above ground), and for randomly selected sample trees, chosen with a probability proportional to basal area, tree heights were also measured. On average, 10 sample plots were measured in each stand.

The standwise estimated stem volumes and tree heights from field measurements collected between 1999 and 2002 were adjusted to year 2003 to match data acquisition using the growth functions according to Söderberg (1986). For the objectively inventoried stands, the stem volume was in the range of 30–620 $m^3\ ha^{-1}$ (average 286 $m^3\ ha^{-1}$) and the basal area weighted mean tree height (in the following referred to as tree height) was in the range of 6.2–27.5 m (mean 19.2 m). The stands varied between 0.6 and 11.2 ha in size with an average of 2.9 ha. The estimated accuracy, in terms of standard error, was on average 9% of stem volume and 2% of tree height, at stand level.

Laser Data

The Swedish airborne laser scanning system TopEye was operated from an altitude of 430 m above ground level with a flight speed of 25 $m\ s^{-1}$. The laser data used were acquired on Aug. 9, 2003 with a beam divergence of 1.0 mrad, a wavelength of 1,064 nm, a pulse frequency of 7,000 Hz, a scan frequency of 17 Hz, and a scan angle of $\pm 20°$. Approximately 2.5 laser measurements per square meter were registered with a variation in density of returned laser pulses depending on overlaps in flight line swaths. The first and last return pulses were recorded.

High Pulse Density

Initially, all laser measurements were classified as ground or nonground return using a progressive triangular irregular network (TIN) densification method (Axelsson 1999, 2000) in the TerraScan software (Soininen 2004). The ground returns were connected in a TIN which was used for interpolation to a digital elevation model (DEM) with a resolution of 1×1 m. The vertical distance from the estimated ground elevation of the DEM was derived for each return classified as nonground (in the following referred to as canopy height). The laser returns were further classified as vegetation returns and nonvegetation returns on the basis of the canopy height. A laser return was classified as vegetation return if the canopy height was >1 m and greater than a threshold of 10% of the maximum canopy height of the forest stand. Several variables were derived on the basis of the canopy heights by the exclusive use of first return pulse data to consider one transmitted laser beam as one sample. For each forest stand, the distribution of canopy heights from vegetation returns was used to derive the 10th, 20th, . . . , 90th, 95th, and 100th height percentile and the mean height (e.g., Lefsky et al. 1999, Means et al. 2000). Also, the ratio between the number of vegetation returns and the total number of returns was derived (in the following referred to as laser-derived canopy density) (e.g., Næsset 2002, Holmgren 2004).

Reduced Pulse Density

To evaluate the effect of different pulse density on estimation accuracy of tree height and stem volume at stand level, laser data were thinned using TerraScan software. Altogether, thinning at 15 different levels were performed by removing laser returns from the high pulse density laser data. The thinning was carried out by allowing a minimum horizontal distance of 1, 2, . . . , 15 m between adjacent laser returns. The thinned laser data were classified as ground or nonground returns (Axelsson 1999, 2000) using the same parameter settings as for the classification of high pulse density laser data. The ground returns for each thinning level were connected in a TIN and then converted to a DEM. Consequently, 15 different DEMs were created. Subsequently, the laser variables were derived for each thinning level by applying the same method as described previously for the high pulse density laser data. In the evaluation procedure two different DEMs for each thinning level were used, i.e., the DEM created from the high pulse density laser data and the DEM created from the corresponding thinned laser data. Hence, the effect of different DEMs on estimation accuracy of tree height and stem volume at stand level could be examined. Statistics calculated for the high pulse density laser data and the 15 different thinning levels are presented in Table 1.

Table 1. Pulse density and proportion of classified ground returns using high pulse density laser data and thinned laser data, based on 70 stands

Thinning (m)	No. of transmitted pulses (ha^{-1})			Classified ground returns (%)
	Min	Max	Average	Average
No thin.	6552	46780	24911	12
1	2332	4356	3820	15
2	952	1335	1214	18
3	444	722	619	18
4	306	453	405	16
5	213	308	280	16
6	154	225	206	16
7	123	170	157	16
8	103	135	124	17
9	89	112	99	17
10	75	89	82	18
11	62	77	69	18
12	53	64	59	19
13	46	60	51	20
14	39	50	45	22
15	33	48	40	22

Statistical Analysis

Regression analysis was used to relate the laser-derived variables to tree height and stem volume at stand level. To evaluate the estimation accuracy of the forest variables, regression models were developed using the high pulse density laser data. The models developed were then used in a sensitivity analysis of estimation accuracy, where the pulse density was reduced.

A linear regression model describing the relation between tree height and laser derived height, at stand level, was developed according to Holmgren (2004):

$$h_i = \alpha_0 + \alpha_1 \cdot h_{\text{laser},i} + \varepsilon_i + \delta_i, \qquad (1)$$

where h_i is the tree height in m for stand i, α_0 and α_1 are the regression coefficients, and $h_{\text{laser},i}$ is the laser-derived height for stand i. The variable ε_i is the random error for the true stem volume and δ_i is the sampling error for the ith stand. The random variables ε_i and δ_i were assumed to be independent and normally distributed with zero expectations and variances $\sigma_1^2 = \text{var}(\varepsilon_i)$ and $\sigma_{2i}^2 = \text{var}(\delta_i)$. Furthermore, a multiple linear regression model describing the relation between stem volume and laser-derived height and canopy density, at stand level, was developed according to Næsset (1997):

$$\ln(v_i) = \alpha_0 + \alpha_1 \cdot \ln(h_{\text{laser},i}) + \alpha_2 \cdot \ln(d_{\text{laser},i}) + \varepsilon_i + \delta_i, \qquad (2)$$

where v_i is the stem volume in $\text{m}^3\ \text{ha}^{-1}$ for stand i, α_0, α_1, and α_2 are the regression coefficients, and $d_{\text{laser},i}$ is the laser-derived canopy density, for the ith stand. The variables $h_{\text{laser},i}$, ε_i, and δ_i have the same meaning and properties as in model 1. The logarithmic transform was needed to obtain a linear relationship between stem volume and the predictor variables. The estimated stem volumes were corrected for logarithmic bias using the average stem volume from the field data divided by the average of predicted stem volume as a correction factor (Holm 1977).

The predictor variables included in the regression models were selected on the basis of significance levels of the regression coefficients, adjusted coefficients of determination, and residual plot studies. The regression coefficients were estimated by means of ordinary least squares. To ensure that the regression functions were not overfitted, cross-validation was performed by calculating the square root of the ratio between the predicted sum of squares of residuals and the ordinary sum of squares of residuals, denoted q (Weisberg 1985).

When thinned laser data are used, the independent variables of height percentiles are expected to be less-stable measures of standwise tree height in comparison with the laser-derived mean height. Therefore, separate regression functions for the laser-derived height percentiles and mean height were established from the developed models. For each thinning level in the sensitivity analysis, both the DEM created from high pulse density laser data and the DEM created from thinned laser data were used. In addition, an accuracy evaluation of the DEMs created from thinned laser data compared with that using high pulse density laser data was performed and expressed in terms of RMSE, standard deviation (SD), and bias.

Throughout the analysis the estimation accuracy assessment of the tree height was expressed in terms of RMSE (in m) and the stem volume was expressed in terms of relative RMSE (in %). The relative RMSE was obtained through retransformation of the logarithmic SD about the regression function. Finally, the RMSE for the tree height and the stem volume estimation were adjusted for sampling error according to Fransson et al. (2001).

Results

Statistics for the tree height regression functions derived from model 1 using high pulse density laser data are shown in Table 2. The estimation accuracy expressed in RMSE was found to be about 0.8 m for the 90th height percentile and about 0.9 m for the mean height derived from the laser data. The adjusted coefficient of determination exceeded 95%, i.e., that either the 90th height percentile or mean height separately explained most of the variation of the tree height. Statistics for the logarithmic stem volume regression functions derived from model 2 using high pulse density laser data are outlined in Table 3. The estimation accuracy of stem volume using the regression functions showed an RMSE of about 13% for both the 90th height percentile and the mean height. The q-values calculated from the cross-validation test confirmed that the empirical regression functions derived from the models 1 and 2 were not overfitted ($1.02 \leq q \leq 1.04$). Also, the residual plot studies showed no trends, indicating homogeneity of variance about the regression functions. As shown in Figures 2 and 3, the forest variables are plotted against the estimated forest variables from high pulse density laser data, using the regression functions derived from models 1 and 2.

The results from the sensitivity analysis in which laser-derived variables were based on a reduced pulse density are presented in Figures 4, 5, and 6, with fitted trend lines. As shown in Figure 4, there is a general trend of increasing RMSE for tree height estimation with increasing thinning level using model 1. The RMSE was found to be in the range of 0.7 to 1.8 m. A major finding is the rapid increase in RMSE at thinning levels >10 m (corresponding to a

Table 2. Root mean square error (RMSE), adjusted coefficient of determination (R^2_{adj}), regression coefficients ($\alpha_0 - \alpha_1$), and corresponding q-value for tree height regression functions derived from model 1 using high pulse density laser data, based on 70 stands

Model	Laser derived height	RMSE (m)	R^2_{adj} (%)	α_0	α_1	q
(1)	90th perc.	0.775 (0.819)	97.5	0.414[a]	1.03	1.02
	Mean	0.908 (0.946)	96.8	0.937	1.32	1.02

All regression coefficients except [a]($P = 0.26$) are significant at 5% significance level ($P \leq 0.05$). Numbers in parentheses are not adjusted for sampling error.

Table 3. Root mean square error (RMSE), adjusted coefficient of determination (R^2_{adj}), regression coefficients ($\alpha_0 - \alpha_2$), and corresponding q-value for logarithmic stem volume regression functions derived from model 2 using high pulse density laser data, based on 70 stands

Model	Laser derived height	RMSE (%)	R^2_{adj} (%)	α_0	α_1	α_2	q
(2)	90th perc.	12.9 (14.2)	93.1	1.11	1.68	1.78	1.03
	Mean	13.1 (14.4)	93.0	1.86	1.55	1.53	1.04

All regression coefficients are significant at 5% significance level ($P \leq 0.05$). Numbers in parentheses are not adjusted for logarithmic bias and sampling error.

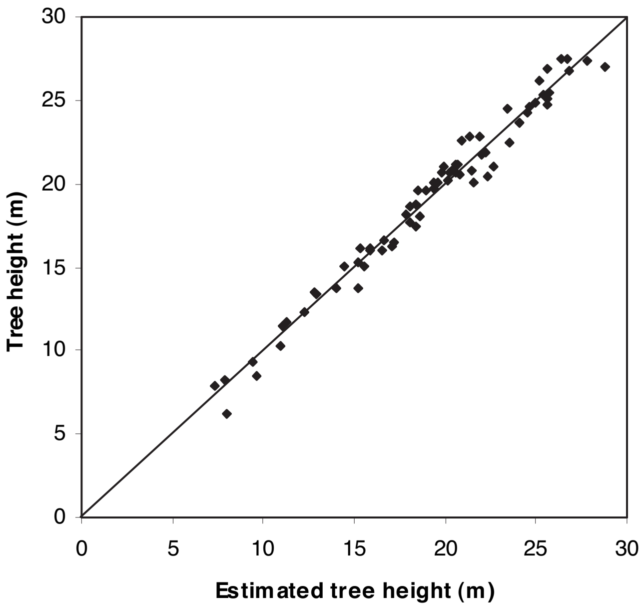

Figure 2. Tree height plotted against estimated tree height from high pulse density laser data using the regression function derived from model 1, with a 1-to-1 reference line, for 70 stands. The laser-derived height is the 90th height percentile.

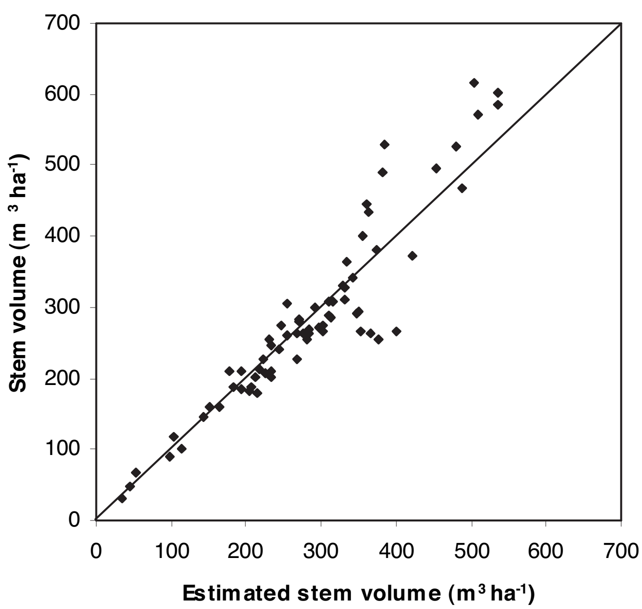

Figure 3. Stem volume plotted against estimated stem volume from high pulse density laser data using the regression function derived from model 2, with a 1-to-1 reference line, for 70 stands. The laser-derived height is the 90th height percentile.

pulse density less than 80 returns ha^{-1}; see Table 1) when the thinned DEM is used for tree height estimation. On the other hand, by using the DEM created from the high pulse density laser data the RMSE of tree height estimation increased modestly from 0.7 to 1.1 m as an effect of the reduced pulse density. Overall, it can be observed that the laser-derived 90th height percentile (Figure 4a) gave a slightly better estimation accuracy of tree height compared with that using mean height as the predictor variable (Figure 4b). A two-sided t-test also revealed that the 90th height percentile performed better than the mean height over the entire range of thinning levels ($P < 0.01$).

As shown in Figure 5, the RMSE for stem volume estimation increased with increasing thinning level using model 2. By reducing the pulse density the RMSE increased from about 13% to 29%. As observed for the tree height estimation a substantial increase in RMSE for stem volume estimation at thinning levels greater than 10 m could be noticed when using the thinned DEM. Using the DEM created from the high pulse density laser data, the RMSE of stem volume estimation increased from 13% to 23% as an effect of the reduced pulse density. A two-sided t-test showed that the mean height performed slightly better than the 90th height percentile over the entire range of thinning levels ($P < 0.01$) only in the case of using the DEM created from the high pulse density laser data.

As shown in Figure 6, the RMSE for the created DEMs increased from about 0.1 to 2.4 m as an effect of increased thinning level. Furthermore, the increase in RMSE is quite modest and unbiased up to a thinning level of 10 m. When the pulse density decreased even further, i.e., thinning level >10 m, the increase in RMSE is more rapid and the DEMs become positively biased.

Discussion

The estimation accuracy of forest variables at stand level using laser data from the Swedish TopEye system with different pulse densities was investigated. Using high pulse density laser data (about 2.5 laser measurements per square meter) the estimation accuracies for tree height and stem volume derived from models 1 and 2, respectively, were found to be in agreement with previous studies (e.g., Næsset et al. 2004). The results are based on well-managed forest stands with coniferous stem volume >70% and soil type till. The reason for this stratification is that a mixture of coniferous and deciduous species or a mixture of good and poor site quality index may degrade the estimation accuracy seriously (e.g., Næsset 2002). Moreover, regarding the stem volume estimation, a number of observations are clearly overestimated (Figure 3). This overestimation can be explained by the dense understory consisting of hazel (*Corylus avellana* L.) and oak (*Quercus robur* L.) in pine dominated stands. Consequently, the canopy density derived from laser data is overestimated. However, these multilayered stand

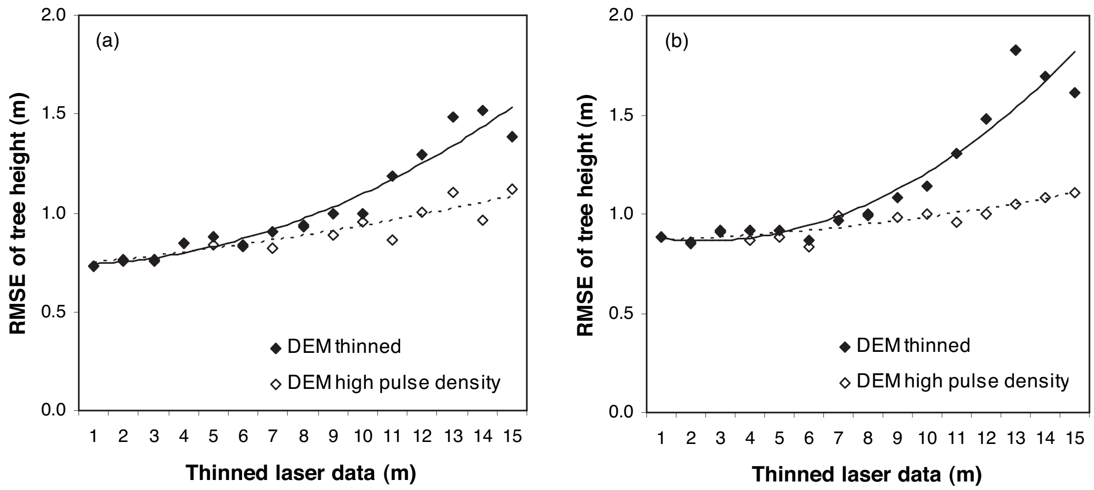

Figure 4. RMSE of tree height regression functions derived from model 1 using thinned laser data and the DEM created from thinned or high pulse density laser data based on 70 stands. The laser-derived heights in a and b are the 90th height percentile and the mean height, respectively.

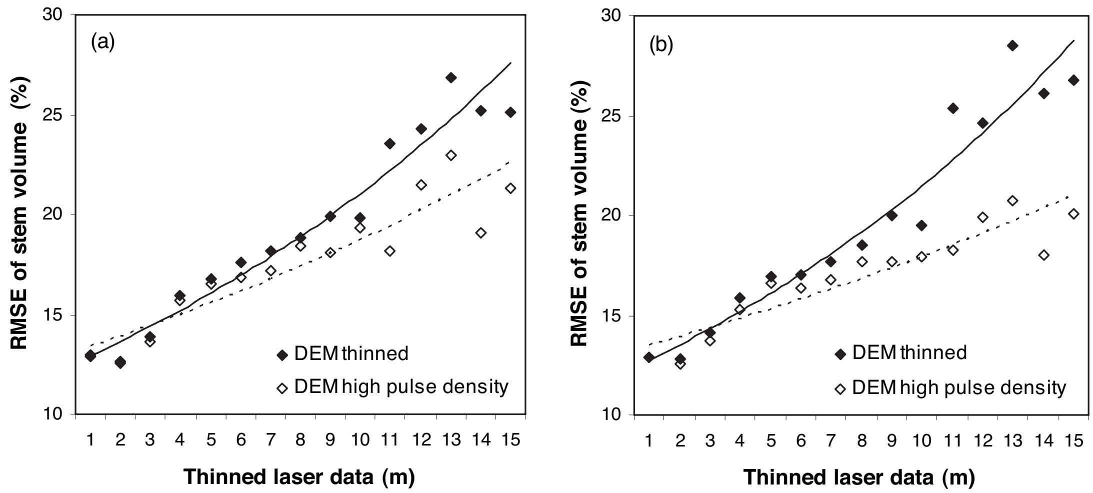

Figure 5. Relative RMSE of logarithmic stem volume regression functions derived from model 2 using thinned laser data and the DEM created from thinned or high pulse density laser data based on 70 stands. The laser-derived heights in a and b are the 90th height percentile and the mean height, respectively.

structures can be recognized in the shape of the height distribution when high pulse density laser data are used (Maltamo et al. 2005). Besides stratification and removal of understory, forest variable estimation at stand level can be slightly improved by applying a grid-based approach (i.e., dividing the stands into grid cells for which the laser-derived variables are calculated) (e.g., Magnussen and Boudewyn 1998, Means et al. 2000, Næsset et al. 2004). Furthermore, the estimation accuracy can, to some extent, be improved by including more independent variables in the developed models. However, the focus of this study was to evaluate the effect on estimation accuracy of forest variables using different laser pulse densities.

A substantial decrease in estimation accuracy of forest tree height and stem volume could be observed when the laser pulse density is reduced from about 25,000 to 40 returns ha^{-1} (Figures 4 and 5). Previous studies, in which the laser pulse density was reduced to about 1,000 returns ha^{-1} showed small or no effect on estimation accuracy (e.g., Holmgren 2004, Maltamo et al. 2006).

As a major result, the RMSE increased rapidly at thinning levels $>$10 m ($<$80 returns ha^{-1}) when the thinned DEMs were used for estimation of tree height (Figure 4) and stem volume (Figure 5). This can be explained by the rapid increase of the systematic error (positive bias) in the DEMs produced at thinning levels $>$10 m (Figure 6). However, up to the thinning level of 10 m, no or small systematic errors could be observed in the thinned DEMs. Consequently, the RMSE for tree height estimation and stem volume estimation, separately, is about the same at each thinning level regardless of whether the thinned DEMs or the DEMs produced from the high pulse density laser data are used.

The quality of a DEM derived from laser data is affected by several factors including classification parameter setting, interpolation method, and grid size. In the present study, these factors are kept constant. Therefore, the decrease in DEM accuracy with increasing thinning level could be explained by the reduction of pulse density. A reduction in pulse density leads to increasing classification and interpolation errors (e.g., Klang and Burman 2005, Anderson et al.

Table 4. Effects on laser system features when collecting data from a platform flying at a greater speed or at a higher altitude. The system dependent variables beam divergence, pulse frequency, scan frequency, and scan angle are kept constant

	Pulse density	Reflected energy	Footprint diameter	Ability to penetrate canopy	Maximum pulse repetition frequency	Swath width	Coverage
Greater speed	decrease	no	no	no	no	no	increase
Higher altitude	decrease	decrease	increase	decrease	decrease	increase	increase

2006). These errors become gradually evident as the thinning level increases. As shown in Table 1, the proportion of classified ground returns increases from about 12% to 22%, indicating less accurate classification of ground and nonground returns as a result of the reduced pulse density. In particular, at thinning levels >10 m the classification errors can mainly explain the positive bias in the thinned DEMs (Figure 6), which affects the estimation accuracy of tree height and stem volume severely. Hence, at low pulse densities the estimation accuracy of tree height and stem volume could be largely improved by having access to a high resolution unbiased DEM.

By using thinned laser data, the independent variable of the 90th height percentile was expected to be a less stable measure of standwise tree height in comparison with the laser-derived mean height. However, for tree height estimation the selection of the 90th height percentile compared with the mean height as predictor variable improved the accuracy. This result might be explained by the fact that the sample size is large enough, even at the thinning level of 15 m.

In contrast with previous studies, in which relatively modest reduction of pulse density was performed (e.g., Holmgren 2004, Yu et al. 2004, Lovell et al. 2005, Maltamo et al. 2006), the laser density was reduced heavily. In Holmgren (2004) and Lovell et al. (2005), the reduction was carried out by a time sequential selection of laser returns, whereas in Maltamo et al. (2006) the reduction was performed in the spatial domain. As the principles for distributing laser measurements on ground differ among laser systems (Wehr and Lohr 1999), the latter approach was adopted in the present study to obtain results independent of the system used. It should be noted, however, that the thinning procedure used is only theoretical.

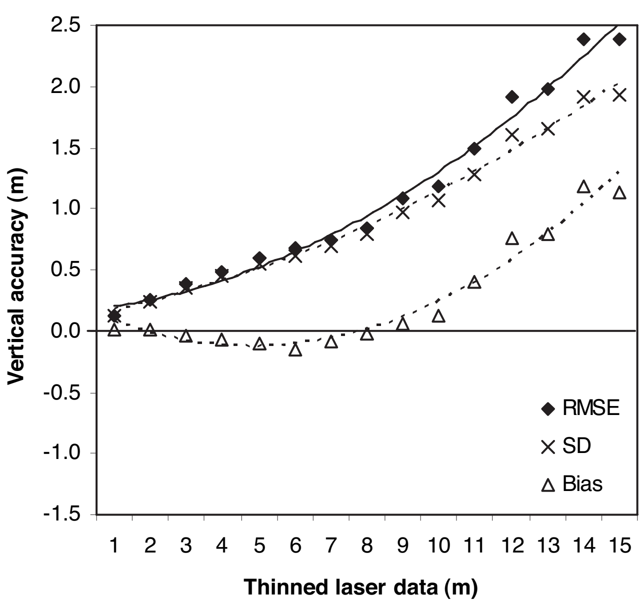

Figure 6. Vertical accuracy in terms of RMSE, SD, and bias of the DEMs derived from thinned laser data based on 70 stands.

In an operational scenario the cost of collecting airborne laser scanner data for forest inventory may be reduced by increasing the flight speed or the flight height (i.e., increasing the coverage capacity per unit time). If the aircraft is flying at a greater speed, the pulse density will decrease without influencing other features such as footprint diameter and ability to penetrate the canopy, given that the system-dependent variables beam divergence, pulse frequency, scan frequency, and scan angle are kept constant. On the other hand, if the aircraft is flying at a higher altitude, several features will be affected (given the above constraints of the system-dependent variables). Besides a reduced pulse density, the amount of reflected energy and the ability to penetrate the canopy decrease. To compensate for the decrease in reflected energy at a higher altitude, the laser instruments have to be designed for greater output power. As a consequence, the maximum pulse repetition frequency will decrease. There is also a physical system limitation in flight altitude, from where it becomes impossible for a laser system to capture laser data without losing the internal order of the emitted laser pulses. In Table 4, the major effects on laser system features when data are collected from a platform flying at a greater speed or at a higher altitude are summarized. As a result of decreased laser pulse density (when increasing flight speed or flight height) the data set will also be more manageable for operational use (e.g., lower computational requirements).

The estimation accuracies of tree height and stem volume decreased with reduced pulse density from 2.5 laser returns per square meter to 15 m horizontal distance between adjacent laser returns. Even though the pulse density was reduced to several meters between adjacent laser returns, the estimation accuracies were equal to or better than those commonly obtained by using conventional forest inventory methods, e.g., aerial photo interpretation. This finding implies that low pulse density airborne laser scanner data could be cost efficient to use in inventory for estimation of forest variables at stand level.

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