ASSESSING EFFECTS OF LASER POINT DENSITY ON BIOPHYSICAL STAND PROPERTIES DERIVED FROM AIRBORNE LASER SCANNER DATA IN MATURE FOREST

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ABSTRACT:

Canopy height distributions were created from small-footprint airborne laser scanner data for mature coniferous forest in two forest areas in Norway. In total, 82 and 70 georeferenced field sample plots and 39 and 38 forest stands were measured in the two areas, respectively. The average sampling densities were 1.2 m^{-2} and 0.9 m^{-2}. Height percentiles, mean and maximum height values, coefficients of variation of the heights, and canopy density at different height intervals above the ground were computed from the laser-derived canopy height distributions from the first return data. The laser point clouds were thinned to approximately 1 point per 4 m^2 (0.25 m^{-2}), 1 point per 8 m^2 (0.13 m^{-2}), and 1 point per 16 m^2 (0.06 m^{-2}). The mean difference and the standard deviation for the differences between laser-derived metrics derived from the original full density laser data and thinned data for the two areas were estimated and compared. For all comparisons, the maximum value of the canopy height distributions differed significantly between the full density laser datasets and the thinned data. The effects of different laser point densities on stand predictions of three biophysical properties of interest were also tested. The average standard deviation for mean tree height, stand basal area, and stand volume predicted at stand level showed only a minor increase by decreasing point density.

1. INTRODUCTION

For economical reasons, optimal specification of fieldwork, sensor, and flight parameters for laser data acquisition is important in practical forest inventory. A number of parameters for specifying airborne laser data acquisition have to be decided upon prior to survey, and they may influence on important properties such as the theoretical number of points per unit area, the ability to derive forest structural information, and survey costs.

In an area-based approach, i.e., individual forest stands are the basic units of the inventories, a large number of explanatory laser variables are extracted from the laser points and used to predict forest biophysical properties. A sampling density of about one laser point per square metre has shown promising results (Næsset, 2002b; Næsset, 2004b). The effects of point density have been assessed in a number of studies (e.g. Holmgren, 2004; Magnusson, 2006; Maltamo et al., 2006; Thomas et al., 2006). A study in Sweden indicated that the errors of predicted mean tree height, basal area, and stem volume did not differ much when the point density was changed from 0.1 to 4.3 m^{-2} (Holmgren, 2004). Holmgren used a footprint diameter of 1.8 m and the large footprint size resulted in overlap between adjacent footprints on the ground. Oversampling may therefore have infulenced on the results. In a Finnish study, where the point densities were 12.7, 6.3, 1.3, 0.6, and 0.13 m^{-2} and the footprint diameter was 40 cm, no effects of point density on stem volume prediction were found (Maltamo et al., 2006). However, the basic dataset in the Finnish study was limited to 32 sample plots with size 0.09 ha. In contrast to the studies mentioned above, Magnusson (2006) found that the RMSE for tree height and stem volume estimation increased when the point density was redused from 2.5 to 0.004 m^{-2}. Many of the variables extracted from the laser point clouds are highly correlated. In addition, if some of these potential laser metrics are more sensitive to point density, then it would be best to select, as independent variables, those laser measures that are least affected by point density.

The objectives of this study were to assess the effects of different laser point densities on laser-derived metrics and to assess how laser point density may affect stand predictions of three biophysical properties of interest, i.e., mean tree height, basal area, and volume. Four different levels of laser point densities were assessed. The results were evaluated using an independent validation dataset.

2. MATERIAL AND METHODS

2.1 Study area

Two forest areas in southeast Norway were selected for this study: a forest area in the municipality of Våler (59°30’N, 10°55’E, 70-120 m a.s.l.) of about 1000 ha, and a forest area in the municipality of Krødsherad (60°10’N 9°35’E, 130-660 m a.s.l.) with size 6500 ha. The study sites in Våler and Krødsherad are hereafter denoted as sites A and B, respectively. The main tree species in the areas were Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). Further details can be found in Næsset (2002b) and (Næsset, 2004b).

The present study was based on two different field datasets from each area: sample plots and forest stands. The sample

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plots were used to assess the effects of different laser point densities on laser-derived metrics and to develop regression models for the three biophysical properties of interest. The forest stands were used to assess the influence of laser point density on the stand predictions for the three biophysical properties.

2.2 Sample plots

In total, 82 sample plots in site A and 70 in site B were distributed systematically in the mature forest across the entire study areas according to regular grids. The areas of the sample plots were 200 and 232.9 m^2 in sites A and B, respectively. The measurements were carried out during the summers 1999 (Næsset, 2002b) and 2001 (Næsset, 2004b). On each plot, all trees with d_{bh} >10 cm were callipered. The d_{bh} was recorded in 2 cm classes. Basal area (G) was computed as the basal area per hectare of the callipered trees. The heights of sample trees were measured by a Vertex hypsometer. Mean height of each plot was computed as Lorey's mean height (h_L), i.e., mean height weighted by basal area. Volume of each tree was computed by means of volume equations of individual trees (Brantseg, 1967; Braastad, 1966; Vestjordet, 1967), with height and diameter as predictor variables. Total plot volume (V) was computed as the sum of the individual tree volumes.

Finally, to synchronize the h_L, G, and V values to the date the laser data were acquired the individual plot values were prorated by means of growth functions (Blingsmo, 1984; Braastad, 1975; Braastad, 1980; Delbeck, 1965). The prorated values were used as ground-truth. A summary of the ground-truth sample plots data is displayed in Table 1.

Differential Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS) were used to determine the position of the centre of each sample plot. The computed plot coordinates had an expected average accuracy of approximately 0.3 m.

2.3 Stand inventory

In site A, 39 stands were selected subjectively in order to represent different combinations of site quality classes and tree species mixtures. Field data were collected during summer 1998 (Næsset, 2002a). The average stand size was 1.7 ha. Each stand was inventoried by intensive sample of plots within each stand. The average number of plots per stand was 20. In site B, 38 large test plots located in subjectively selected stands were used. Ground reference data for the test plots were collected during summer 2001. Each plot was initially supposed to be a quadrat with an approximate size of 61× 61 m, but the actual size varied somewhat. On each of these plots, all trees with size greater than the specified limits were callipered. The large test plots are hereafter denoted stands. The stand data values were synchronized to the date the laser data were acquired by prorating by up to 1.5 years. The prorated values were used as ground-truth. A summary of the ground-truth stand data is displayed in Table 1.

Characteristic	Sample plots Range			Mean	Stands Range			Mean
Site A				*(200 m^2, n=82)*				*(n=39)*
h_L (m)	12.0	-	26.0	18.5	13.6	-	22.9	17.9
G (m^2ha^{-1})	7.5	-	50.6	24.2	12.6	-	38.8	24.9
V (m^3ha^{-1})	53.2	-	632.7	219.2	90.8	-	410.9	216.9
Tree species distribution								
Spruce (%)	0	-	100	54	4	-	94	53
Pine (%)	0	-	100	41	0	-	92	38
Deciduous species (%)	0	-	27	5	1	-	22	9
Site B				*(232.9 m^2, n=70)*				*(n=38)*
h_L (m)	9.9	-	26.0	18.1	12.2	-	24.4	17.9
G (m^2ha^{-1})	5.6	-	57.0	28.1	12.0	-	37.7	25.4
V (m^3ha^{-1})	29.6	-	674.8	251.2	83.0	-	378.9	224.5
Tree species distribution								
Spruce (%)	0	-	100	38	1	-	100	50
Pine (%)	0	-	100	58	0	-	98	41
Deciduous species (%)	0	-	29	4	0	-	40	9

[a] h_L=Lorey's mean height, G=basal area, V=volume.

Table 1. Summary of field inventory of sample plots and stands [a].

2.4 Laser scanner data

A Piper PA31-310 aircraft carried the ALTM 1210 laser scanning system (Optech, Canada). The laser scanner data were acquired 8 and 9 June 1999 for site A (cf. Næsset, 2002b; Næsset and Bjerknes, 2001) and in the period between 23 July and 1 August 2001 for site B (cf. Næsset, 2004b). A summary of the laser scanner data is presented in Table 2.

All the first return laser points were spatially registered to the DTM derived from the last return echoes according to their coordinates. The relative height of each point was computed as the difference between the height of the return and the interpolated terrain surface height. Only these first returns were used for further analysis. Points that hit outside the plots and stands were excluded from further analysis.

2.5 Reduction of laser point density

In order to investigate the effects of laser point densities on the laser-derived metrics and on the predicted biophysical stand properties, the point clouds were thinned. The point clouds were thinned from about 1.2 m^{-2} and 0.9 m^{-2} for site A and B, respectively, to approximately 1 point per 4, 8, and 16 m^2 (0.25, 0.13, and 0.06 m^{-2}) by randomly selecting one point within grid cells with the respective sizes (4, 8, and 16 m^2). This thinning method was employed to insure a fairly regular distribution of the retained points. A similar approach has also been used in other studies (e.g. Magnusson, 2006).

	Number of obs.	No. of transmitted pulses (m^{-2}) Range			Mean	No. of canopy hits (m^{-2}) [a] Range			Mean	Mean rate of penetration (%)
Site A										
Sample plots	82	0.73	-	1.62	1.12	0.33	-	1.34	0.80	28
Stands	39	1.04	-	1.41	1.19	0.60	-	1.33	0.88	26
Site B										
Sample plots	70	0.40	-	2.00	1.03	0.24	-	1.62	0.80	23
Stands	38	0.50	-	1.71	0.89	0.31	-	1.62	0.70	22

[a] Canopy hits: laser points with a height value of >2 m.

Table 2. Summary of characteristics of first return laser scanner data for sample plots and stands.

2.6 Computations

For each sample plot and stand inventoried in field, height distributions were created for those laser points that were considered to belong to the tree canopy, i.e., points with a height value of >2 m. Percentiles for the canopy height for 10% (h_{10}), 50% (h_{50}), and 90% (h_{90}) were computed. In addition, also the maximum (h_{max}) and mean values (h_{mean}) and the coefficient of variation (h_{cv}) of the canopy height distributions were computed. Furthermore, several measures of canopy density were derived. The range between the lowest laser canopy height (>2 m) and the 95% percentile for the canopy height distribution was divided into 10 fractions of equal length. Canopy densities were computed as the proportions of laser hits above fraction #0 (>2 m), 1, . . ., 9 to total number of points. The densities for fraction #1 (d_1), #5 (d_5), and #9 (d_9) were selected for further studies.

To assess how different laser point densities influenced on the laser-derived metrics, differences between corresponding metrics derived for the different alternatives were computed for each sample plot. The standard deviations of the differences were also computed to assess the stability of the respective metrics. Separate comparisons between laser scanner data with different point densities were made.

To assess the accuracy of laser-based predictions of mean tree height, basal area, and volume based on different laser point densities, we followed the two-step procedure proposed by Næsset & Bjerknes (2001) and Næsset (2002b) by (1) relating the three biophysical properties of interest to the laser data of the sample plots in the two sites using regression analysis, and by (2) applying the estimated regression models to predict corresponding values of the test stands. In addition, the differences between predicted values of the biophysical stand properties and ground-truth values were computed. The standard deviations of the differences were also calculated.

In the regression analysis, multiplicative models were estimated as linear regressions in the logarithmic variables. Stepwise selection was performed to select variables to be included in these models. No predictor variable was left in the models with a partial F statistic with a significance level greater than 0.05. The standard least-squares method was used (Anon., 1989).

Separate predictions were made for the two sites and the different laser point densities. In the prediction, each stand was divided into grid cells. Laser canopy height distributions were created for each cell and the biophysical properties were predicted at cell level using the estimated equations and the derived laser metrics. Finally, predicted values at stand level were computed as mean values of the individual cell predictions. The mean differences between predicted biophysical stand properties and ground-truth and corresponding estimates of the standard deviations of the differences were derived.

3. RESULTS

3.1 Laser-derived metrics

Height percentiles

None of the mean differences for the percentiles (h_{10}, h_{50}, h_{90}) between the full density data and the thinned data in site A and only one in site B were found to be statistically significant. In both sites and for all comparisons the standard deviations for the differences of the percentiles between the full density data and the thinned data increased by decreasing point densities, i.e., from 0.25 m^{-2} to 0.06 m^{-2}. In general, the standard deviations were smallest in site A (Table 3).

Height maximum, mean, and variability

For all comparisons, the maximum values of the canopy height distributions (h_{max}) differed significantly between the full density laser data and the thinned data. The differences increased with decreasing point density for all comparisons. The h_{max} values were always highest for the full density data.

Only one of the comparisons of the differences for the mean height values (h_{mean}) between the full density laser data and the thinned data were found to be statistically significant.

The variability of the canopy height distributions expressed by the coefficient of variation (h_{cv}) did not differ significantly in any of the comparisons between the laser point intensities.

For both h_{max}, h_{mean}, and h_{cv}, the standard deviations of the differences increased with decreasing laser point density for all the comparisons. The standard deviations of the differences were smaller in site B compared to site A.

Canopy density

For both sites, the differences of canopy densities (d_1, d_5, and d_9) between the full density laser data and the thinned data were found to be statistically significant in four of the comparisons. In all of the comparisons the standard deviations for the differences of the canopy densities between the full density data and the thinned data increased by decreasing point densities, i.e., from 0.25 to 0.06 m^{-2}.

Metrics[b]	0.25 points m^{-2}			0.13 points m^{-2}			0.06 points m^{-2}		
	Mean *D*		S.D.	Mean *D*		S.D.	Mean *D*		S.D.
Site A									
h_{10} (m)	0.15	ns	1.14	-0.06	ns	1.68	0.34	ns	2.80
h_{50} (m)	-0.13	ns	0.81	-0.31	ns	1.29	-0.24	ns	1.94
h_{90} (m)	-0.10	ns	0.77	-0.06	ns	1.21	0.10	ns	1.73
h_{max} (m)	-0.96	***	1.12	-1.66	***	1.27	-2.53	***	1.88
h_{mean} (m)	-0.04	ns	0.50	-0.20	ns	0.87	0.00	ns	1.46
h_{cv} (m)	0.35	ns	3.42	1.88	ns	6.37	0.88	ns	11.41
d_1 (%)	-1.89	**	4.91	-1.97	ns	6.78	-1.46	ns	10.80
d_5 (%)	-2.53	***	5.11	-2.86	**	6.54	-0.76	ns	11.59
d_9 (%)	0.22	ns	4.03	0.66	ns	4.51	4.36	***	6.85
Site B									
h_{10} (m)	-0.06	ns	1.00	-0.08	ns	1.78	0.20	ns	2.35
h_{50} (m)	-0.34	**	0.78	-0.15	ns	1.19	-0.27	ns	1.78
h_{90} (m)	-0.18	ns	0.55	-0.28	ns	1.10	-0.24	ns	1.62
h_{max} (m)	-0.93	***	0.90	-1.30	***	1.23	-2.06	***	1.61
h_{mean} (m)	-0.18	*	0.48	-0.22	ns	0.80	-0.22	ns	1.37
h_{cv} (m)	0.88	ns	3.41	1.26	ns	5.52	1.01	ns	10.72
d_1 (%)	-2.51	***	3.83	-2.74	**	6.59	0.06	ns	10.33
d_5 (%)	-2.99	***	4.46	-2.48	*	6.47	-1.60	ns	12.57
d_9 (%)	0.08	ns	4.54	0.09	ns	6.21	1.24	ns	8.89

[a] Level of significance: ns = not significant (>0.05). *< 0.05; **< 0.01; ***< 0.001.

[b] h_{10}, h_{50}, and h_{90} = percentiles of the laser canopy heights for 10%, 50%, and 90%; h_{max} = maximum laser canopy height; h_{mean} = arithmetic mean of laser canopy heights; h_{cv} = coefficient of variation of laser canopy heights; d_1, d_5, and d_9 = canopy densities corresponding to the proportions of laser hits above fraction # 1, 5, and 9, respectively, to total number of returns (see text).

Table 3. Differences (*D*) between laser-derived metrics of different point densities and standard deviation for the differences (S.D.) based on data from site A (200 m^2) and from site B (232.9 m^2) sample plots [a].

3.2 Regression models

To assess effects of laser point density on the estimated regression models used in the two-stage inventory, stepwise regression analysis based on the 82 and 70 field training plots, for sites A and B respectively, was carried out to create relationships between the three biophysical properties of interest (h_L, G, and V) and the laser-derived metrics. The regression analysis was carried out using all points, 0.25, 0.13, and 0.06 m^{-2}, respectively. Separate models were estimated for the two sites. When all laser points were used, the selected log-log regression models explained 62-87% and 80-92% of the variability inherent in the log-transformed responses for the two sites.

However, when the lowest point density was used, the model fit was poor. In the model for basal area (G), only 45% and 73% of the variability were explained by the models for sites A and B, respectively. The selected models, R^2, and RMSE when using all points in sites A and B are presented in Table 4. The selected models were slightly different for the other point densities. The models contained from one to three explanatory variables.

Response variable[a]	Expl. variables[b]	R^2	RMSE	κ
Site A				
$\ln h_L$	$\ln h_{10}$, $\ln h_{90}$	0.87	0.07	1.6
$\ln G$	$\ln h_{90}$, $\ln d_5$	0.62	0.25	1.5
$\ln V$	$\ln h_{mean}$, $\ln d_1$	0.71	0.27	1.9
Site B				
$\ln h_L$	$\ln h_{90}$	0.93	0.06	1.0
$\ln G$	$\ln h_{mean}$, $\ln d_1$	0.80	0.20	2.2
$\ln V$	$\ln h_{mean}$, $\ln d_1$, $\ln h_{90}$	0.90	0.20	6.9

[a] h_L=Lorey's mean height (m), G=basal area (m^{2}ha^{-1}), V=volume (m^{3}ha^{-1}).

[b]h_{10} and h_{90}=percentiles of the laser canopy heights for 10% and 90% (m); h_{mean} =arithmetic mean of first return laser heights (m); d_1 and d_5 =canopy density corresponding to the proportion of laser hits above fraction # 1 and 5, respectively, to total number of first returns (see text).

Table 4. Selected models for biophysical properties (response variables) from stepwise multiple regression analysis using

metrics derived using all points on the plots in site A and B as explanatory variables.

All the models selected to be the “best” ones for G and all the models except one for V were based on laser-derived variables related to canopy height and variables related to canopy density. The models for h_L were mainly based on canopy height variables. For all the 24 models developed, i.e., all possible combinations of point density (four densities) and sites (sites A and B) for each of the three variables (h_L, G, and V), at maximum three explanatory variables were selected. Multicollinearity issues were addressed by calculating and monitoring the size of the condition number (κ). None of the selected models had a condition number greater than 6.9, indicating that there was no serious collinearity inherent in the selected models (Weisberg, 1985). All the models developed using the plots in site B accounted for a larger proportion of the variability inherent in the log-transformed responses compared to the models developed using the plots in site A.

3.3 Stand level predictions

The mean and the standard deviations for the differences between predicted mean height (h_L), basal area (G), and volume (V) and ground-truth values for the 39 and 38 stands in sites A and B respectively, are presented in table 5. The mean difference between the full density data and the thinned data varied between densities. However, no clear pattern was found.

The standard deviations for the differences increased in all except five cases when the point density decreased. Two of these five exceptions were for h_L and two were for V. The standard deviations of h_L did only increase to a minor extent when the point density decreased. The standard deviations for the differences were smallest in site B compared to site A in all except two cases.

Response variable[a]	1.2 points m^{-2}		0.25 points m^{-2}		0.13 points m^{-2}		0.06 points m^{-2}	
	Mean *D*	S.D.	Mean *D*	S.D.	Mean *D*	S.D.	Mean *D*	S.D.
Site A								
h_L (m)	-0.03	0.97	-0.01	0.96	-0.05	1.07	-0.06	1.15
G (m^2 ha^{-1})	-0.30	2.67	-0.08	2.73	0.01	3.37	-0.93	3.59
V (m^3 ha^{-1})	2.78	30.11	3.02	29.70	3.09	37.30	-6.01	39.10
Site B								
h_L (m)	-0.35	0.55	-0.33	0.61	-0.06	0.85	-0.35	0.72
G (m^2 ha^{-1})	1.74	3.19	1.78	2.99	1.68	3.05	0.93	3.58
V (m^3 ha^{-1})	8.94	27.80	7.24	26.52	12.41	28.19	2.34	38.23

Table 5. Mean differences (D) and standard deviation for the differences (S.D.) between laser-derived and observed Lorey’s mean height (h_L), basal area (G), and volume (V) in sites A and B when using all points (1.2 m^{-2}), 0.25 m^{-2}, 0.13 m^{-2}, and 0.06 m^{-2}.

4. DISCUSSION

The major findings of this study indicate that:

1) The maximum values of the canopy height distributions (h_{max}) differed significantly between the full density laser data and the thinned data. The differences increased with decreasing point density. In most cases the variability of h_{max} was larger than for the intermediate and upper height percentiles (h_{50}, h_{90}). A higher variability associated with h_{max} has also been found in other studies (Næsset, 2004a; Næsset and Gobakken, 2005). Since h_{max} is seriously affected by point density it should be avoided in practical applications.

2) The standard deviations for the differences for all the derived laser metrics increased by decreasing laser point density, i.e., from 0.25 m^{-2} to 0.06 m^{-2}.

3) For other variables than h_{max}, no clear pattern of the mean differences between the laser metrics derived from full density data and the thinned data could be found.

4) Even if one of the prediction models only explained a quite low proportion of the variability (45%), the effects of reducing point density on the predicted mean height (h_L), basal area (G), and volume (V) at stand level were quite small.

When the laser point density was reduced by thinning to imitate data acquisitions with lower point densities, a random selection of points was carried out. A random selection of points within grid cells of size 4, 8, and 16 m^2 was carried out in order to maintain a fairly regular spatial distribution of the retained points. However, the modelled ground surface was all the time the same. Keeping the DTM constant might influence the results, although other studies indicate that this effect probably is small. Goodwin et al. (2006) indicated that the predicted surface closely matched the field measured even when a point density of 0.18 m^{-2} was used. Magnusson (2006) found the RMSE of the terrain model to be quite low and unbiased up to a thinning level of 0.01 m^{-2}.

To conclude, the results of this study may indicate that the average point density used for the area-based operational forest stand inventory in Scandinavia utilizing airborne laser could be reduced from the current point density of around 1 m^{-2} to 0.06 m^{-2} without seriously reducing the quality of the inventory results. The effects of varying the point density reported here should, however, be verified on different forest types and in other regions than those considered here.

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