EFFECTS OF FOREST GROWTH ON LASER DERIVED CANOPY METRICS

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ABSTRACT:

In the current research, we present the results from a growth detection study in young forest and mature pine-dominated forest located on poor sites. Canopy height distributions were created from small-footprint airborne laser scanner data collected over 87 georeferenced field sample plots. The size of each plot was 300-400 m^2. The laser data were acquired in 1999 and 2001, and none of the plots had been subject to any harvests or serious natural disturbances in the period between the two laser data acquisitions. Canopy height distributions were created from first pulse data. Height percentiles (10%, 50% and 90%), mean and maximum height values, and canopy density at three different height intervals above the ground were computed from the laser-derived canopy height distributions. Corresponding metrics derived from the laser data acquired in 1999 and 2001 were compared. All metrics derived from the first pulse data differed significantly between data acquired in 1999 and 2001 in the young forest and seven of eight metrics differed significantly in the mature forest. The mean values for the difference in mean height and maximum height were 1.24 and 1.11 m in young and 0.43 and 0.22 m mature forest, respectively.

1. INTRODUCTION

Monitoring of timber resources, biomass and carbon stocks might be one of several major directions of future utilization of small-footprint laser data in forests. With an objective of detecting possible vegetation change Sweda et al. (2003) made two temporally separated airborne laser profiling transects flown at five-year interval along a NS-oriented 600 km transect across the boreal forest of western Canada. Yu et al. (2004) were the first to demonstrate the applicability of small footprint, high sampling density airborne laser scanners for boreal forest change detection, i.e. the estimation of forest growth and monitoring of harvested trees. The first change detection studies based on laser scanner data over forest indicate a large potential of multi-temporal data for forest monitoring.

The objective of the present study was (1) to analyse the effect of forest growth at plot level over a short time period on laser-derived metrics typically used in forest inventory and (2) to assess how these effects are influenced by forest type.

2. MATERIALS AND METHODS

2.1 Study area

This study was based on data from a forest inventory in southeast Norway conducted in the municipality of Våler (59°30′N, 10°55′E, 70–120 m a.s.l.). The size of the inventory was approximately 1000 ha. Compared to average forest conditions in Norway, the terrain was considered as quite flat with gentle slopes. The main tree species were Norway spruce [*Picea abies* (L.) Karst.] and Scots pine (*Pinus sylvestris* L.). Further details about the study area can be found in Næsset (2002b). Sample plots were used to assess the effects of forest growth on laser-derived canopy height and density metrics derived from laser data acquired in 1999 to 2001.

2.2 Field data

Field data were collected during summer of 1998 (see Næsset, 2002a). Since the laser data were acquired in 1999 and 2001 (see below), the area were revisited in field in December 2001 to verify that plots had not been subject to any harvests or serious natural disturbances. However, it is likely that some natural mortality had occurred during the 3–4 year period.

In this study, the plots with young forest ("stratum I") and mature forest with poor site quality ("stratum II") were analyzed. In total, 87 circular sample plots were distributed systematically throughout the entire 1000 ha study area according to a regular grid. The size of each plot was 300 m^2 in stratum I and 400 m^2 in stratum II.

On each plot, all trees with diameter at breast height (d_{bh})>4 and >10 cm were callipered on young and mature plots, respectively, which conforms to ordinary inventory practice in Norway. Basal area (G) was computed as the basal area per hectare of the callipered trees. The heights of sample trees selected with probability proportional to stem basal area at breast height using a relascope 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. Total plot volume (V) was computed according to the tree volume tariff method (Husch et al., 1993) by calculating the sum of the individual tree volumes for trees with d_{bh}>4 cm and d_{bh}>10 cm, respectively. h_L, G, and V were prorated by up to 3.8 years using growth models (Blingsmo, 1984; Braastad, 1975; Braastad, 1980; Fitje and Vestjordet, 1977) to correspond to the dates on which the 1999 and 2001 laser data were acquired. These prorated values were used as ground reference. A summary of the ground-truth plot data is displayed in Table 1.

	1999					Mean
Characteristic	Range			Mean	Growth	2001
Young forest – stratum I (n=53)						
h_L (m)	6.5	-	21.2	13.6	0.9	14.5
G (m^2ha^{-1})	9.7	-	41.4	24.5	2.9	27.4
V (m^3ha^{-1})	36.3	-	460.1	178.6	28.6	207.2
Tree species distribution (%)						
Spruce	0	-	100	53		
Pine	0	-	97	34		
Deciduous species	0	-	69	13		
Mature forest, poor site quality – stratum II (n=34)						
h_L (m)	11.4	-	21.5	16.1	0.2	16.4
G (m^2ha^{-1})	9.4	-	29.5	19.1	0.8	19.9
V (m^3ha^{-1})	56.4	-	273.8	148.7	8.3	157.0
Tree species distribution (%)						
Spruce	0	-	89	29		
Pine	0	-	100	66		
Deciduous species	0	-	21	5		

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

Table 1. Summary of sample plot reference data [a]

Differential GPS and Global Navigation Satellite System (GLONASS) were used to determine the position of the centre of each sample plot. A Javad Legacy 20-channel dual-frequency receiver observing pseudorange and carrier phase of both GPS and GLONASS was used. Another Javad Legacy receiver was used as base station. The distance between the plots and the base station was approximately 19 km. Coordinates were computed by postprocessing in an adjustment with coordinates and carrier phase ambiguities as unknown parameters using both pseudorange and carrier phase observations. The estimated accuracy of the planimetric plot coordinates (x and y) ranged from <0.1 to 2.5 m with an average of approximately 0.3 m. Further details are given by Næsset (2002a).

2.3 Laser scanner data

Laser scanner data for this specific study were acquired 8 and 9 June 1999, and 16 and 17 July 2001 (leaf-on canopy conditions). A Piper PA31-310 aircraft carried the ALTM 1210 laser scanner system. The pulse repetition frequency was 10 kHz on both occasions. The average flying altitudes were approximately 700 m a.g.l. in 1999 and 840 m a.g.l. in 2001, and the average footprint densities were 1.1 m^{-2} and 0.9 m^{-2}. According to standard procedures, pulses that were transmitted at scan angles that exceeded 14° and 15° in 1999 and 2001, respectively, were excluded from the final datasets.

Processing of the laser data was accomplished by the contractor (BN Mapping, Norway). Planimetric coordinates (x and y) and ellipsoidic height values were computed for all first and last returns. The last return data were used to model the ground surface. In a filtering operation on the last return data undertaken by the contractor using a proprietary routine, local maxima assumed to represent vegetation hits were discarded. A triangulated irregular network (TIN) was generated from the planimetric coordinates and corresponding height values of the individual terrain ground points retained in the last pulse dataset. Individual TIN models were made of the 1999 and 2001 laser data. The ellipsoidic height accuracy of the TIN models was expected to be around 25 cm (Kraus and Pfeifer, 1998; Reutebuch et al., 2003).

For both the 1999 and the 2001 laser data, all first return observations (points) were spatially registered to the TIN according to their coordinates. Terrain surface height values were computed for each point by linear interpolation from the TIN. The relative height of each point was computed as the difference between the height of the first return and the terrain surface height.

Observations with a height value less than 2 m were excluded from the dataset to eliminate ground hits and the effect of stones, shrubs, etc. from the tree canopy datasets (Nilsson, 1996). Pulses that hit outside these objects were excluded from further analysis.

2.4 Computations

In this study, height distributions were created from laser pulses classified as canopy hits (>2 m, see above) for each plot inventoried in field, and 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}) of the height distributions were computed. Furthermore, several measures of canopy density were derived. The range between the lowest laser canopy height (>2 m) and the maximum canopy height was divided into 10 fractions of equal length. Canopy densities were then computed as the proportions of laser hits above fraction #0 (>2 m), 1, . . ., 9 to total number of pulses. The densities for fraction #1 (d_1), #5 (d_5), and #9 (d_9) were selected for further studies.

The mean differences between data acquired in 2001 and 1999 of the investigated height and density-related metrics were compared *within* different strata by means of paired t-tests to assess how forest growth influenced on the laser-derived metrics. The mean differences between the data acquired in 2001 and 1999 were also compared *between* strata to assess how these metrics were influenced by forest type. Correspondingly, the variances of the differences between laser data acquired on the two occasions were compared for different strata by means of F tests.

In the comparisons of the eight laser-derived metrics within and between strata, eight t-tests or F tests were accomplished simultaneously. In order to control the total Type I error, Bonferroni tests were applied (Miller, 1981). Thus, the level of significance for each of the eight tests was $\alpha/8$.

3. RESULTS

Height percentiles: First, laser-derived canopy height and density metrics were computed for the 87 sample plots. For the first pulse height distribution percentiles (h_{10}, h_{50}, h_{90}), all the mean differences between data acquired in 2001 and 1999 were found to be statistically significant. The differences ranged from 0.40 to 1.32 m (Table 2). All of the differences were found to be statistically significant (p>0.05) when the comparisons between forest types were made (Table 3).

The standard deviations for the differences of the percentiles h_{10}, h_{50}, h_{90} between laser data acquired in 2001 and 1999 ranged from 0.33 to 0.72 m for the sample plots (Table 2). None of the variances for the differences were found to be statistically significant (p>0.05) when the comparisons between forest types were made (Table 3). Both the mean differences and the standard deviations for the differences were larger in the young forest (stratum I) as compared to the mature pine forest on poor sites (stratum II).

Metrics[b]	*D*, first pulse		
	Mean		S.D.
Young forest - stratum I (n= 53 sample plots)			
h_{10} (m)	1.00	***	0.72
h_{50} (m)	1.31	***	0.48
h_{90} (m)	1.32	***	0.46
h_{max} (m)	1.11	***	0.86
h_{mean} (m)	1.24	***	0.42
d_1 (%)	0.06	***	0.04
d_5 (%)	0.11	***	0.05
d_9 (%)	0.01	**	0.02
Mature forest, poor site quality - stratum II (n= 34 sample plots)			
h_{10} (m)	0.43	**	0.67
h_{50} (m)	0.48	***	0.39
h_{90} (m)	0.40	***	0.33
h_{max} (m)	0.22	NS	0.74
h_{mean} (m)	0.43	***	0.29
d_1 (%)	0.05	***	0.05
d_5 (%)	0.05	***	0.03
d_9 (%)	0.01	*	0.02

[a] Level of significance (Bonferroni test, α/8): 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 laser canopy height; 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 pulses (see text).

Table 2. Differences (*D*) between first pulse laser scanner data from 2001 and 1999, respectively, for laser-derived metrics of sample plots and standard deviations (S.D.) for the differences [a]

Height maximum and mean: The maximum values of first pulse canopy height distributions (h_{max}) did not differ significantly between the data acquired in 2001 and 1999 for mature forest dominated by pine (stratum II) (Table 2). The mean differences between data acquired in 2001 and 1999 were 1.11 m in stratum I and 0.22 m in stratum II. The differences for the plots differ significantly between the two strata (Table 3). The standard deviations were 0.86 m in stratum I and 0.74 m stratum II.

The mean height values of the first pulse data (h_{mean}) showed similar patterns as did the height percentiles. The mean differences between laser data acquired in 2001 and 1999 were 1.24 m in stratum I and 0.43 m in stratum II. The differences were found to be statistically significant (p>0.05). The differences across data acquired in 1999 and 2001 differed significantly between young forest and mature forest dominated by pine (Table 3). The standard deviations for the differences in mean values between data acquired in 2001 and 1999 were 0.42 m in stratum I and 0.29 m in stratum II. The standard deviations for the differences in mean height values tended to be smaller than the corresponding standard deviations for percentiles and maximum values.

Canopy density: For the first pulse canopy densities (d_1, d_5 and d_9), the mean differences ranged from 0.01% to 0.11% (Tables 2). The density variables varied significantly between data acquired in 1999 and 2001 for all comparisons. The differences between data acquired in 2001 and 1999 differed significantly between young forest and mature pine forest for d_5 (Table 3) The standard deviations for differences between data acquired in 2001 and 1999 ranged between 0.02% and 0.05% for all comparisons and were smallest for d_9.

Metrics	$\bar{D}_I - \bar{D}_{II}$	S.D.$_I$-S.D.$_{II}$[d]
h_{10} (m)	**	NS
h_{50} (m)	***	NS
h_{90} (m)	***	NS
h_{max} (m)	***	NS
h_{mean} (m)	***	NS
d_1 (%)	NS	NS
d_5 (%)	***	NS
d_9 (%)	NS	NS

[a] Roman subscript refers to stratum.
[b] Level of significance (Bonferroni test, α/8): NS = not significant (>0.05); *< 0.05; **< 0.01; ***< 0.001.
[c] 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 laser canopy height; 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 pulses (see text).
[d] Variance comparison by F tests.

Table 3. Comparisons between strata of mean differences ($\bar{D}$) and standard deviations for the differences (S.D.) between laser derived metrics from laser data acquired in 2001 and 1999 for the sample plots[a,b,c]

4. DISCUSSION

Detection of forest growth by means of laser scanning is important with respect to future use of LIDAR in large-area timber resource and carbon stock monitoring. To the very best of our knowledge, the only study dealing with determination of forest growth and laser scanning so far is the work by Yu et al. (2004) where single trees were detected. Yu et al. (2004) developed an object-oriented tree-to-tree matching algorithm. Out of 83 field-checked harvested trees, 61 could be automatically detected. All mature harvested trees were detected and it was mainly the smaller trees that caused problems. The precision of the estimated height growth, based on field checking or statistical analysis, was about 5 cm at stand level and 10-15 cm at plot level. However, the practical laser-based inventory procedure proposed by Næsset and Bjerknes (Næsset and Bjerknes, 2001) and Næsset (2002b) and area-based measurement are more suitable for large-area monitoring than tree-to-tree matching due to the large amount of data needed for single tree measurements.

In the present study, changes at 300-400 m^2 plots over a two-year period were assessed and the major findings of this study are that height percentiles and mean values of the first pulse data from 2001 were higher than corresponding values derived from 1999 data, and that even certain canopy density measures may be suitable to detect forest growth.

The first pulse measurement of h_{max} was not suitable for detecting forest growth, at least not in the slow-growing mature pine forest. This may be due to the fact that larger sampling errors are associated with the maximum value than, for example, the height percentiles (Næsset, 2004). This was also observed in the present data. The standard deviations for the differences between maximum values were larger than corresponding standard deviations for the other height-related metrics.

In this study, a growth period of two years was analyzed. In e.g. ordinary growth and yield studies or national forest inventories the changes in five year periods are usually applied. More research should be carried out to study how short growth-periods that can be used in such studies. If the time period is too short – especially for low productive forest types – the growth might not be detected due to other error sources.

In spite of the uncertainties related to the mortality and the length of the growth period, forest growth for different forest types can be revealed by laser-derived metrics at plot level. However, to improve the potential of laser-scanning in growth detection, it should be evaluated (1) how effective laser-scanning is for growth detection for other forest types and (2) in entire stands instead of small plots, and (3) the suitability of other laser derived metrics than those considered here and (4) of last pulse data should be investigated.

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