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Thinning- and tree-growth-caused changes in canopy cover and stand height and their estimation using low-density bitemporal airborne lidar measurements – a case study in hemi-boreal forests

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ABSTRACT

Repeated airborne laser scanning (ALS) measurements during leaf-on and leaf-off phenophases were studied. A 15 km × 15 km test site located in northern Estonia was used that included a reference set of stands, and 870 stands with thinning carried out before, between, and after two ALS flights. The decrease in ALS-based canopy cover estimate (CC_{ALS}) caused by thinning was similar for the leaf-off and leaf-on phenophases, and for different height thresholds. The point cloud height percentile (H_{Px}) values increased in almost all thinned stands, and the increase was present for the leaf-off and leaf-on phenophases. ALS point cloud metrics (skewness, kurtosis, mode, and canopy relief ratio) showed no response to thinning (p-value >0.05). Stand-dominating species had no significant influence on H_{Px} increment or CC_{ALS} change using the leaf-on data (p-value >0.05). The minimum height filter for pulse return selection had a substantial influence on H_{Px} increment in stands thinned between the two ALS measurements. Ground points are usually excluded from H_{Px} calculation, but for stand-level analyses, their inclusion can provide additional information.

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Change detection; commercial thinning; forest management; forest height increment; canopy cover; repeated airborne laser scanning

Introduction

A common practice of forest management involves commercial thinning, for the purpose of increasing forest growth and promoting forest health (Kocoloski, Griffin, & Matthews, 2011). Smaller changes, such as thinning that removes 20% or less of the basal area, have a relatively small impact on the spectral signature (Olsson, 1994) in multispectral satellite images. With small-scale disturbances, the recovery time of the forest canopy is also shorter – the tree crowns grow denser and wider on account of the free space. Olsson (1994) showed that within four to five years the thinning effect on forest reflectance decreases, showing a forest signature similar to that before the treatment. Depending on the method of the thinning – upper-layer thinning, understory removal, high-intensity, or low-intensity – the treatment could also have a negligible effect on canopy cover (CC), altering the variability but leaving the stand mean spectral signature unchanged.

Airborne laser scanning (ALS) has immensely increased in usage over the past few decades in forest inventories. Originally designed for terrestrial mapping and construction of digital terrain models (DTM), ALS was soon discovered to have potential in monitoring and predicting forest inventory variables (Large & Heritage, 2009). Most laser scanners work in the near-infrared (NIR) spectral range, being able to penetrate the green foliage and vegetation to provide data throughout the vertical forest cross-section (Bottalico et al., 2017; Næsset, 1997a). The ability to gather such vertical data enables the prediction of the structure variables of forests (Ellis, Griscom, Walker, Gonçalves, & Cormier, 2016; Korpela, 2008; Næsset & Gobakken, 2005; Wing et al., 2012). Such data can also be used for forest planning and management (Valbuena, Eerikäinen, Packalen, & Maltamo, 2016), including monitoring forest height growth (Lang, Arumäe, Laarmann, & Kiviste, 2017; Yu, Hyyppä, Kukko, Maltamo, & Kaartinen, 2006), canopy cover estimation (Korhonen, Korpela, Heiskanen, & Maltamo, 2011), assessing biomass increment (Ene et al., 2017; Guerra-Hernández et al., 2016; Kotivuori, Korhonen, & Packalen, 2016; Næsset, Bollandsås, Gobakken, Solberg, & McRoberts, 2015; Temesgen, Strunk, Andresen, & Flewelling, 2015), mapping clear-cuts or other disturbances (Andersen, Reutebuch, McGaughey, d'Oliveira, & Keller, 2014; Nijland et al., 2015; Vastaranta et al., 2013), and mapping tree mortality or windthrow (Nyström, Holmgren, Fransson, & Olsson, 2014).

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As with multitemporal satellite images, similar change detection methods can be applied to ALS data. Zhao et al. (2018) demonstrated a strong correlation between the field-measured and lidar-based forest height growth and biomass increment predictions, and with the availability of high-density ALS data (>7 points per square metre, p m^{-2}), change detection at the single-tree level could be realistic, provided with bi-temporal high-density ALS datasets. Hevia et al. (2016) carried out thinning experiments with different intensities in four pure and even-aged maritime pine (*Pinus pinaster* Aiton) stands and found that canopy cover estimates were good indicators for thinning detection. Such reliable methods for mapping of disturbances and forest growth are necessary for national forest stock reporting, but can also enable pre-targeting of forest inventory fieldwork. The amount of timber obtained from commercial thinning in Estonia is 12.2% of the total felling volume and 20% of the total felling area (Valgepea, Sims, Raudsaar, & Timmusk, 2017). The Estonian Land Board carries out routine laser scanning measurements over one-quarter of Estonia in every second year (Maa-amet, 2006). Bitemporal measurements in similar phenological conditions occur in every fourth year. Such sparse (<1 p m^{-2}) point clouds are influenced by changes in forest canopy and could, therefore, be used for state-level disturbance monitoring.

Lang and Arumäe (2018) used low-density ALS measurements to show that in Estonian hemiboreal forests, there is a moderate relationship between thinning intensity and canopy cover change. In this study, we used low-density nationwide bitemporal ALS measurements from routine measurements to study methods for detecting thinning using data from leaf-off (from bud swelling until leaf unfolding) and leaf-on (final leaf-unfolding period) phenophases (Lukasová, Lang, & Škvarenina, 2014). For the analysis, the forest management inventory database and the Estonian state forest thinning cutting register were used. The study focussed mainly on questions (1) how do the ALS point cloud metrics change over time in thinned stands, (2) what is the effect of phenology on detecting thinning cuttings and forest height growth using sparse ALS point clouds from bitemporal measurements, (3) are thinning events detectable if both ALS measurements are done after thinning?

Methods and materials

Test site

The Aegviidu 15 × 15 km site in the northern part of Estonia (59° 19′ 20” N, 25° 35′ 36” E) was first measured in 2008 (Anniste & Viilup, 2010). The test site is mainly dominated by coniferous hemi-boreal forests, with Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L.) the most common tree species. A smaller proportion of the forests are dominated by deciduous species like birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) and European aspen (*Populus tremula* L.). The most common site types by the classification schema of Lõhmus (2004) are *Myrtillus*, *Polytrichum-Myrtillus*, and *Rhodococcum*. The forests are typical of the hemi-boreal region (Jõgiste et al., 2017), with Norway spruce in the lower and mid-layer. Most of the forests in the area are managed by the Estonian State Forest Management Centre (RMK).

Airborne LiDAR data for the Aegviidu test site

ALS measurements were carried out by the Estonian Land Board at the Aegviidu test site using a Leica ALS50-II scanner. The repeated measurements were carried out four years after the first measurements. The ALS measurements (Table 1) for the leaf-off phenophase were taken during the national topographic mapping program for DTM construction in early spring 2009 (ALS_{2009}) and the middle of spring 2013 (ALS_{2013}). The leaf-on summertime ALS measurements were taken during routine forest inventory mapping flights (Maa-amet, 2006) in 2008 and 2012 (ALS_{2008}, ALS_{2012}). Pulse repetition frequency varied between the measurements (Table 1) and the scan angle was limited to less than 28°. The influence of flight altitude and scan angle on the ALS metrics was not studied; because we used the database of routine scanning, data and repeated measurements taken at different altitudes for comparison were not available.

FUSION freeware tools (McGaughey, 2014) were used for the ALS data processing. A point cloud for each forest stand in the forest inventory database was extracted using the PolyClipData module.

Canopy cover is the proportion of vertical projections of crowns covering the ground surface, with the crowns considered solid shapes with no gaps (Jennings, Brown, & Sheil, 1999). The ALS-based

Table 1. ALS leaf-on and leaf-off measurement specifications and descriptive data.

Dataset	Flight year	Point density (p m^{-2})	Flight altitude (m)	Laser footprint Ø (m)	First to all echos ratio	Pulse freq. (kHz)	Scanning freq. (Hz)	Flight dates
Leaf-on								
ALS_{2008}	2008	0.45	2400	0.53	0.70	103.0	46.8	11 Jul, 27 Jul, 01 Sep
ALS_{2012}	2012	0.25	3800	0.86	0.74	61.0	20.9	20 Jun – 04 Jul
Leaf-off								
ALS_{2009}	2009	0.45	2400	0.54	0.66	93.0	32.0	15 May, 26 May
ALS_{2013}	2013	0.23	2400	0.54	0.68	46.7	32.0	3–4 May

proxy for canopy cover $CC_{ALS} = N_{p,canopy}/N_p$ was calculated for each stand using a threshold method (Korhonen, Ali-Sisto, & Tokola, 2015; Smith et al., 2009), where N_p was the count of returns in point cloud and $N_{p,canopy}$ was the count of returns from the canopy. The threshold was first set to breast height (1.3 m) from the ground, and all echoes above the threshold were used when calculating CC_{ALS}. This was done to reduce the saturation effect in dense forests, as was shown by Arumäe and Lang (2018). The second computation of CC_{ALS} was done using an increased threshold of 8 m above the DTM. Point cloud height distribution statistics and metrics were calculated using a minimum height filter similar to Næsset (1997b), excluding returns below 1.3 m. For an additional comparison, no minimum height filter was used, and all echoes were included for percentile calculations. For the change detection experiment, the studied point cloud height metrics were at the 25th, 50th, 80th, and 95th percentiles (H_{P25}; H_{P50}; H_{P80}; H_{P95}) based on previous experiments (Arumäe & Lang, 2016; Lang & Arumäe, 2018; Lang, Arumäe, & Anniste, 2012; Lang, Arumäe, Lükk, & Sims, 2014). In addition to the point cloud height percentiles, we studied the skewness, kurtosis, and mode value of the ALS point cloud height distribution and canopy relief ratio (CRR) (McGaughey, 2014):

$$\mathrm{CRR} = \left(\overline{H_{\mathrm{ALS}}} - H_{ALS,min}\right)/\left(H_{ALS,max} - H_{ALS,min}\right), \tag{1}$$

which was calculated using the mean ($\overline{H_{\mathrm{ALS}}}$), minimum ($H_{\mathrm{ALS,min}}$), and maximum ($H_{\mathrm{ALS,max}}$) heights of echoes for each forest stand.

Forest inventory and management data

Forest stand data for the Aegviidu test site were obtained from the Estonian Forest Register. The database contains forest stand map and tables with records of forest age, standing volume per unit area, basal area, relative density, site type, tree species composition, and other common forest inventory variables. The selection rules of forest stands to increase the sample size were similar to those of Lang and Arumäe (2018). The most important criteria were the size limit of at least 1 ha and more than 750 ALS returns for each stand polygon. The forest management data and commercial thinning data were obtained from the RMK database. The dates recorded in the RMK database for each thinning operation do not correspond to the actual felling work but are the dates of the field inspections, which may have been carried out several months after the actual thinning. To exclude the falsely dated thinning operations, the extracted ALS point clouds and available orthophotos were visually checked to determine the actual starting and ending times in relation to the ALS measurements.

The final dataset contained information of 870 thinned forest stands with a mean size of 2.49 ha. Most of the stands were dominated by Scots pine (398), birch (195), or Norway spruce (191). The rest of the stands in the sample were dominated by deciduous species such as European aspen, grey alder, or black alder (Table 2). The thinning is usually carried out from below and also from the dominant layer with the aim to increase the growth space for the remaining trees with the best stem properties. An additional 2,113 reference stands with no thinning were used for comparison (Table 2) with a mean size of 2.51 ha.

Statistical analysis

For the mean value comparison of CC_{ALS} or H_{P80} for different data acquisitions, a paired t-test was used after accepting the variance homogeneity with the F-test.

We applied two linear models, M_1 (2) and M_2 (3):

$$Y = b_0 + b_1 \cdot x + e, \tag{2}$$

$$Y = b_0 + b_1 \cdot x + SP + e, \tag{3}$$

where Y was CC_{ALS} and H_{P80} using on dataset ALS_{2008} or ALS_{2009}, x was CC_{ALS} or H_{P80} correspondingly on dataset ALS_{2012} or ALS_{2013}, SP was the dummy-variable component (Fox & Weisberg, 2011), b_0 and b_1 were the model parameters, and e was the error term. The dummy-variable component SP was implemented for regression model as $c_1{\cdot}x_1 + c_2{\cdot}x_2 + \ldots + c_k{\cdot}x_k$, where the dummy-variables x_1, x_2 …, x_k were defined as follows: x_1 equals 1 for Scots pine-dominated stand and 0 for other dominating species, x_2 equals 1 for Norway spruce dominated stand and 0 for other dominating species, x_k equals 1 for the kth dominated stand and 0 for other dominating species and c_1, c_2 …, c_k are parameters.

To estimate the significance of the additional variable SP in M_2, analysis of variances (ANOVA) was used. The F statistic for model comparison was as follows (Faraway, 2005):

$$F = \frac{(RSS_{M1} - RSS_{M2})/(p_2 - p_1)}{RSS_{M2}/(n - p_2)}, \tag{4}$$

where RSS_{M1} and RSS_{M2} are the residual sums of squares for the models M_1 and M_2, respectively, p_1 and p_2 are the number of parameters for M_1 and M_2, and n is the number of observations.

The influences of thinning year (T_{Year}), site fertility index (H_{100}), and stand age at the time of thinning (A_{Thinning}) on the change in H_{P80} (ΔH_{P80}) were studied using T_{Year} as a factor, using the generalized additive models (function gam, Mixed GAM Computation Vehicle package):

$$\Delta H_{P80} = a_0 + a_1 \cdot T_{Year} + a_2 \cdot A_{Thinning} + a_3 \cdot H_{100} + e, \quad (5)$$

where a_x are the model parameters and e is the error term.

The factor level 0 was assigned to stands with T_{Year} before 2008, and for the rest of the stands, factor value was calculated as T_{Year} – 2007. This yielded factor levels 1–7 (Table 4).

Statistical analyses were carried out using R software (R Core Team, 2014).

Results

Canopy cover estimates in reference stands

The mean CC_{ALS} estimate for the reference stands from ALS_{2008} and ALS_{2012} revealed no significant change in value over the four years – the mean difference was only 0.4% (interquartile range 5.6%), and the t-test showed no statistically significant difference (p-value >0.05). The mean CC_{ALS} calculated for the reference stands using leaf-off data ALS_{2009} was 2% larger (p-value <0.05) than for ALS_{2013}, and the CC_{ALS} mean difference was dependent on stand-dominating species (Eq. 4, p-value <0.05). The interquartile range of CC_{ALS} was also larger for the leaf-off dataset (10.9%). The dominating species was not significant for leaf-on data when tested using the ANOVA model comparison (Eq. 4, p-value >0.05). There was a relatively large CC_{ALS} variation for both leaf-off and leaf-on phenophases in the reference stands, mostly due to the random character of the point cloud formation (Arumäe & Lang, 2018), and partly due to differences in leaf-off phenological stages in the case of springtime measurements (ALS_{2009} and ALS_{2013}). A substantial increase in CC_{ALS} by 2012 appeared in younger stands where the height of trees crossed the 1.3 m threshold used for CC_{ALS} calculation, and these stands were excluded from the reference data, similar to the clear-cut areas.

Canopy cover change in thinned stands

The CC_{ALS} for the stands thinned 1 year before the first ALS flight (Figure 1(a,e)), did not change significantly (t-test, p-value >0.05) during the bitemporal ALS measurements. In the stands that were thinned after the later ALS measurement (Figure 1(d,h)) a slight systematic decrease in CC_{ALS} was present. The decrease in CC_{ALS} was statistically insignificant for leaf-off data (p-value >0.05). This decrease in CC_{ALS} is most likely due to natural self-thinning and tree mortality, difference in leaf area index, or differences in scanning setups. In contrast, for leaf-off data, the results were also influenced by the earlier scanning date for ALS_{2013} compared to ALS_{2009}, which resulted in the stands being at different phenological stages.

The mean CC_{ALS} decrease in stands thinned between the two ALS flights was in the same range for both leaf-on (20.7%, interquartile range 15.4–25.1%; Figure 1(b,c)) and leaf-off data (21.5%, interquartile range 16.3–26.9%; Figure 1(f,g); Table 2). The few stands where the CC_{ALS} change was small (Figure 1(f)) were thinned with lower intensity, i.e. less than 20% of the standing wood volume was removed. The CC_{ALS} at the 8 m threshold was statistically significantly smaller compared to the CC_{ALS} at the 1.3 m threshold (for ALS_{2008} 54.3% and 65.1%, ALS_{2009} 50.3% and 62.4%, ALS_{2012} 61.1% and 52.6%, and ALS_{2013} 44.1% and 54.3%, respectively; p-value <0.01), but had no significant advantage in detecting thinning for either leaf-on or leaf-off data. A similar conclusion was made by Lang and Arumäe (2018) for a subsample of the stands using leaf-on data.

Changes in point cloud height distribution

The leaf-on ALS point cloud height percentiles H_{P25}, H_{P50}, H_{P80}, and H_{P95} showed a statistically significant (p-value <0.05) increase between the two bitemporal ALS measurements in thinned stands. The height difference was somewhat larger and more scattered for H_{P25} (Figure 1(i)) compared to higher H_{Px}. The difference between the leaf-off and leaf-on mean height increment was statistically significant (p-value <0.01).

Table 2. The Aegviidu test site characteristics based on forest inventory data. Age – A, stand basal area – G, stand mean height – H, site index – H_{100}. Interquartile range is given in brackets.

Dominating species	A (yrs)	G (m^2 ha^{-1})	H (m)	H_{100} (m)
Thinned stands (n = 870)				
Scots pine	69 (55–80)	22.0 (20–25)	16.7 (14–20)	22.1 (21–25)
Norway spruce	44 (36–52)	18.4 (15–22)	12.9 (10–16)	23.6 (21–25)
Birch	45 (35–55)	18.4 (15–22)	15.4 (12–19)	24.1 (21–25)
Other species	43 (36–49)	23.4 (19–26)	16.6 (14–19)	26.1 (22–28)
Reference stands (**n** = 2,113)				
Scots pine	85 (55–105)	19.4 (17–23)	15.1 (12–19)	18.3 (17–21)
Norway spruce	56 (29–90)	14.1 (11–22)	12.9 (7–22)	22.4 (21–25)
Birch	51 (23–73)	14.4 (7–21)	14.3 (5–20)	21.8 (17–25)
Other species	48 (38–61)	20.7 (17–24)	15.8 (15–20)	24.2 (21–25)

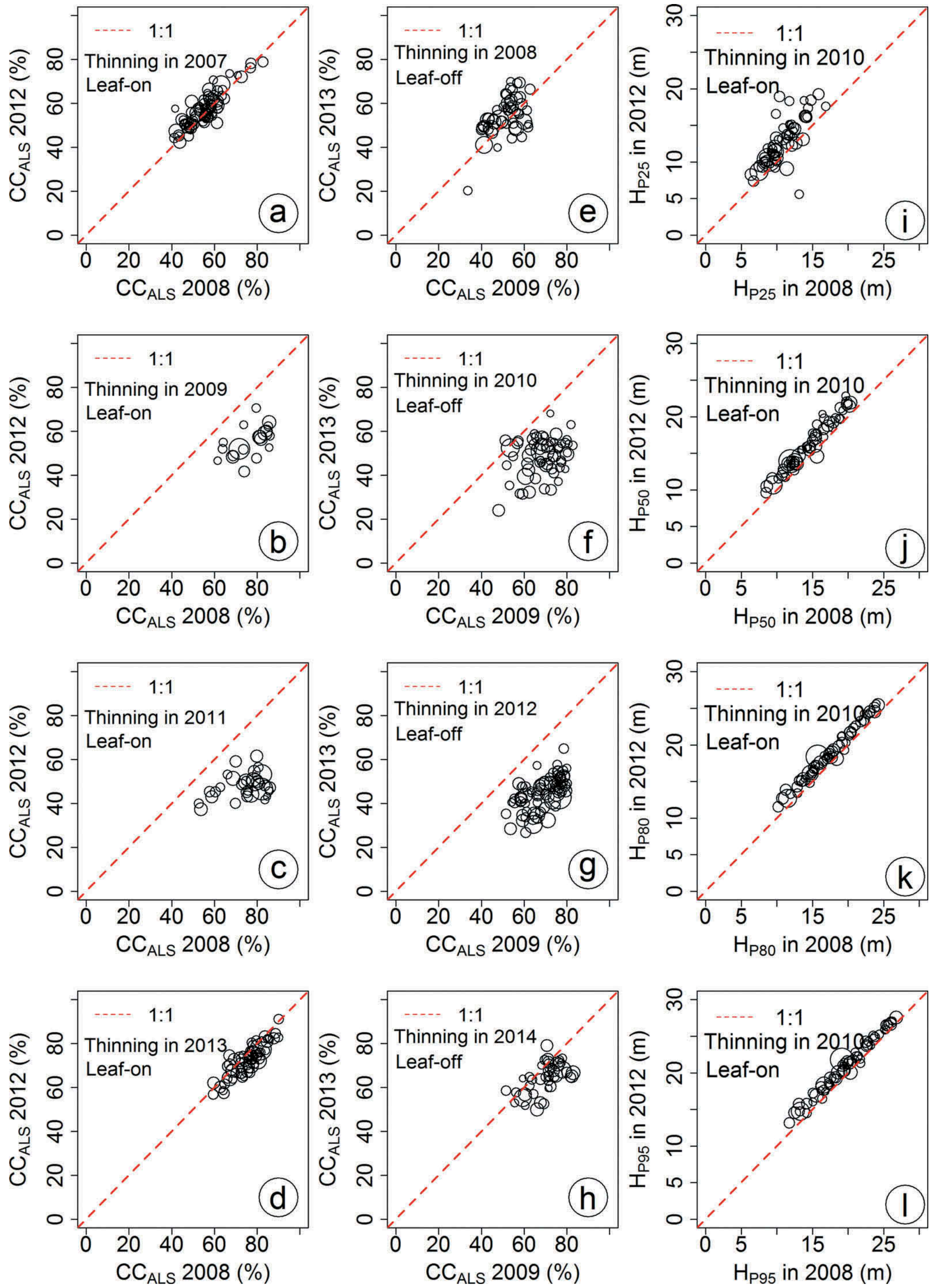

Figure 1. Examples of ALS-based canopy cover proxy (CC_{ALS}) and point cloud height distribution percentiles H_{P25}, H_{P50}, H_{P80}, and H_{P95} over four years with thinning carried out before, in between, and after the ALS measurements. Symbols are scaled to indicate stand size.

Nijland et al. (2015) compared the mean height and 95th percentile difference for thinned stands and found that distance between the height percentiles increased with thinning intensity. However, in our tests, the H_{P50} and H_{P95} difference before and after thinning did not change significantly (p-value = 0.2). The mean increase of H_{P80} for the leaf-off flight pair was 0.73 m, and for leaf-on data, the increase was 1.19 m (Table 3). The smaller increment in the H_{P80} calculated from the leaf-off flight pair is most likely because the first measurements (ALS_{2009}) were carried out in late May, whereas the measurements of ALS_{2013} were taken at the beginning of May (Table 1). Using the leaf-off dataset, the H_{P80} increment was also dependent on species composition; in thinned stands, the H_{P80} mean increment was significantly greater in evergreen coniferous forests compared to deciduous broadleaf species-dominated forests. This is most likely the result of differences in the phenological stages of the deciduous species. According to Ahas,

Table 3. The mean ALS-based canopy cover estimate (CC_{ALS}) and point cloud height distribution 80th percentile H_{P80} from leaf-off and leaf-on seasonal ALS measurements for stands with different thinning years. Standard error (S_e) is given in brackets.

Leaf-on				
Thinning year	$\overline{CC_{ALS}}$ 2008 (%)	$\overline{CC_{ALS}}$ 2012 (%)	$\overline{H_{P80}}$ 2008 (m)	$\overline{H_{P80}}$ 2012 (m)
2007	56.0 (0.9)	57.8 (0.9)	18.7 (0.3)	19.8 (0.3)
2008	57.9 (1.3)	56.7 (1.2)	17.8 (0.4)	18.9 (0.4)
2009	76.6 (1.9)	54.5 (1.4)	16.6 (0.5)	17.6 (0.5)
2010	74.2 (1.0)	55.3 (0.8)	17.2 (0.5)	18.6 (0.5)
2011	74.4 (1.7)	48.9 (1.6)	16.5 (0.5)	18.2 (0.5)
2012	72.8 (0.9)	47.4 (0.8)	14.6 (0.3)	16.3 (0.4)
2013	74.5 (0.9)	71.3 (0.9)	15.7 (0.4)	17.5 (0.4)
Leaf-off				
Thinning year	$\overline{CC_{ALS}}$ 2009 (%)	$\overline{CC_{ALS}}$ 2013 (%)	$\overline{H_{P80}}$ 2009 (m)	$\overline{H_{P80}}$ 2013 (m)
2008	52.3 (1.0)	55.2 (1.4)	17.8 (0.4)	18.3 (0.4)
2009	59.1 (2.5)	53.7 (1.4)	16.3 (0.5)	17.0 (0.5)
2010	68.2 (1.2)	47.9 (1.2)	17.1 (0.5)	18.2 (0.5)
2011	68.9 (1.6)	47.1 (1.2)	16.4 (0.5)	17.6 (0.5)
2012	68.8 (0.9)	45.5 (1.0)	14.6 (0.3)	16.0 (0.3)
2013	68.9 (1.1)	47.9 (1.4)	15.7 (0.4)	17.1 (0.4)
2014	70.1 (1.2)	64.5 (1.1)	16.3 (0.4)	17.1 (0.3)

Jaagus, and Aasa (2000), foliation of birch and other deciduous species in Estonia usually begins in early May and the final-leaf-unfolding phenophase occurs at the end of May, which falls within the bracket of flight times for ALS_{2009} and ALS_{2013}.

There was a systematic increase in H_{Px} of the reference stands similar to that of the thinned forest stands (Figure 2). The mean increase in H_{P80} (0.96 m; S_e = 0.02 m) of the reference stands, based on ALS_{2008} and ALS_{2012}, was significant (p-value <0.01) and slightly less than in the thinned stands (1.19 m; S_e = 0.06 m). This was due to the higher soil fertility (H_{100}) in the thinned stands compared to the reference stands (Table 2). A linear regression model (Figure 2) was fitted for leaf-on flight H_{Px} values of ALS_{2008} and ALS_{2012} for the reference stands. The linear model slope varied from 0.92 to 0.96 and was statistically significant (p-value <0.01; Figure 2). This indicates a greater height increment in younger stands (<30 years) and a smaller height increment in older stands (>60 years), which was also confirmed by a one-sided t-test (p-value <0.05). Stand-dominating species did not impact the H_{Px} change, according to a comparison of linear models (4) (p-value >0.05; Figure 2).

Other point cloud metrics

The other point cloud metrics (skewness, mode, and CRR) were mostly correlated to each other when compared using leaf-on data (R^2 = 0.35–0.64) and also to CC_{ALS} (R^2 = 0.17–0.44), except kurtosis. Surprisingly, the height distribution metrics did not change over the course of four years with structure changes caused by thinning. The four metrics did not show significant differences in their behaviour between the thinned and reference stands (p-value >0.05) and were not influenced by different thinning years except for CRR, which is caused by the calculation being based on the H_{Pmax} and H_{Pmin}.

The influence of thinning year

The model (5) (Table 4) for studying the dependence of ΔH_{P80} on T_{Year}, H_{100}, and $A_{Thinning}$ showed no dependence on T_{Year} for stands thinned before the first ALS data measurement in 2008 for leaf-on data, or for stands thinned before 2009 using leaf-off data. Instead, ΔH_{P80} showed a significant correlation to the stand age at the year of thinning $A_{Thinning}$ and site fertility index H_{100} (Table 4; p-value <0.05). When applied to all the thinned stands, the model (5.2) also showed a dependence of ΔH_{P80} on T_{Year} (Table 4; p-value <0.01). The determination coefficient R^2 increased significantly from 0.34 to 0.44 when a spline fitting (model 5.3) of T_{Year} was used instead of a linear relationship (Table 4). From Figure 3 we also see that the spline fitting was justified considering the shape of the relationship for both leaf-off and leaf-on data. The ΔH_{P80} showed a systematic increase for stands thinned near the second ALS data acquisition in 2012 and 2013 (Figure 3(a,c)). The fitted linear model using thinning year as a factor showed a significant difference in ΔH_{P80} between thinning years before 2007 and after 2007 (Table 4), and in the case of leaf-off data, between thinning years before 2008 and after 2008. Adding the

Table 4. The parameters of model (5) describing the change in the 80th percentile depending on the selection of stands and using leaf-on data. Factor level 0 corresponds to stands thinned before 2008, and the rest are calculated as thinning year – 2007.

Model	$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$	R^2	Model info
M5.1	*13.21*	*−0.006*	−0.013	0.0190	0.26	Model for stands thinned before the year 2007
M5.2	−70.65	0.036	−0.013	0.0255	0.34	Model without any filters to thinning year
M5.3	1.040	8.675 (s)	−0.012	0.0308	0.44	Model using spline fitting (s) on the thinning year
M5.4		0: 0.933 1: −0.149 2: −0.307 3: 0.275 4: 0.627 5: 0.611 6: 0.580 7: 0.438			0.30	Model for studying differences between thinning years. Each factor represents a different thinning year starting from 2008 (1–7). The factor 0 represents stands thinned before 2008.

*The values in italics are statistically insignificant (p-value >0.05).

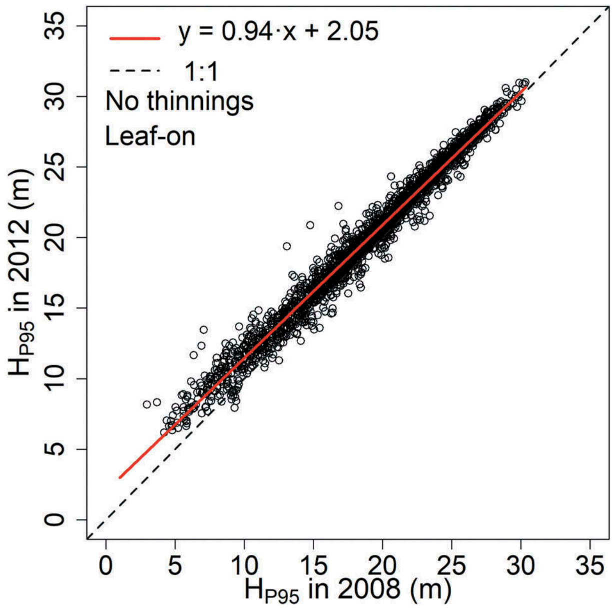

Figure 2. ALS point cloud height distribution percentile H_{P95} from 2008 and 2012 and the fitted linear model in reference stands.

H_{100} and $A_{Thinning}$ to the model increased R^2 from 0.30 to 0.44 using leaf-on data; however, there was no significant increase in the case of leaf-off data.

We also analysed point clouds including the points from below the usual 1.3 m minimum height threshold and found different dependences of ΔH_{P80} on thinning year for the stands thinned between the two ALS measurements. In these point clouds, ΔH_{P80} decreased for the stands compared to those that were thinned before the first or after the latter ALS measurement (Figure 3(b)). A similar analysis for ΔH_{P80} using leaf-off data from ALS_{2009} and ALS_{2013} also indicated a possible decrease, but this was obscured by the influence of phenology.

Discussion

Forest canopy properties have a direct impact on the forest spectral signature measured using passive optical sensors, as well as the distribution of recorded photons from laser pulses. Changes in canopy

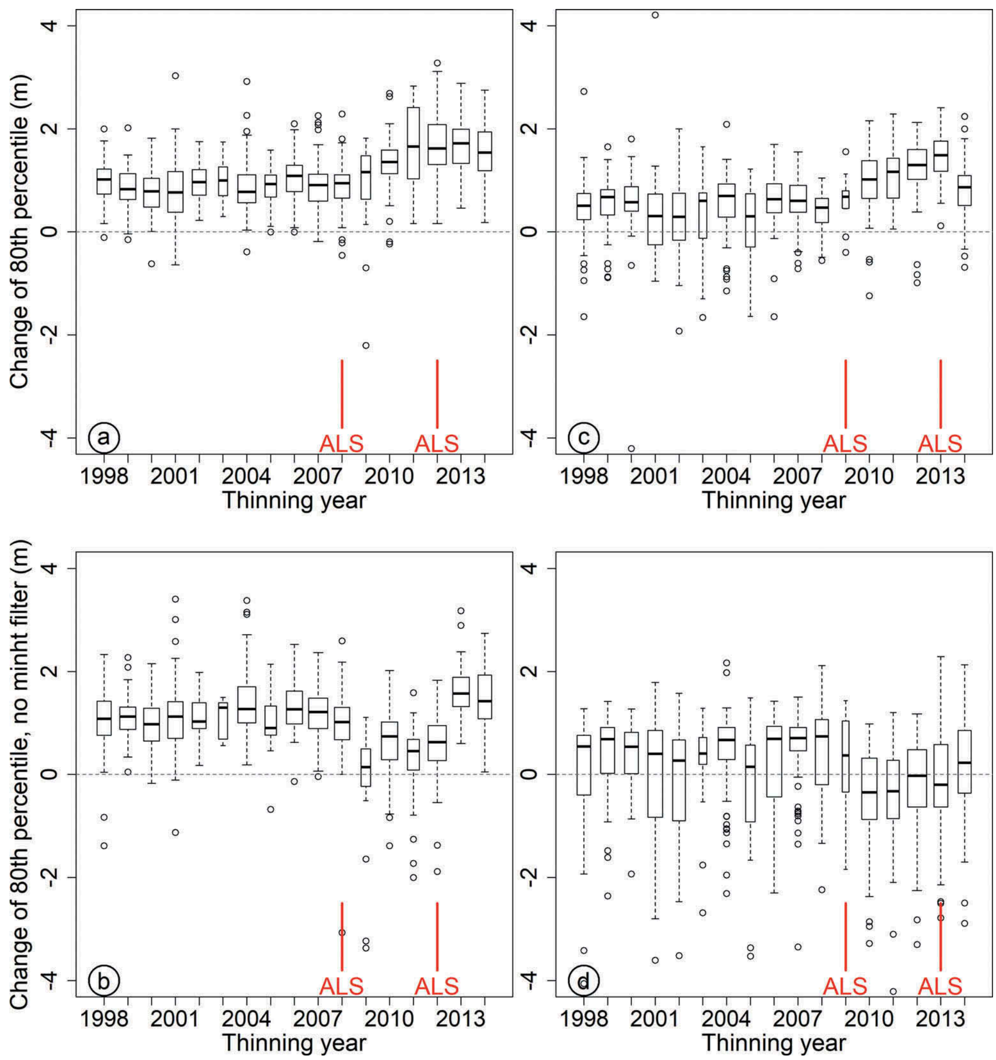

Figure 3. Boxplots showing the median, 25th, and 75th percentiles and individual outliers of the change in 80th percentile of point cloud height distribution using leaf-on data as a function of thinning year: (a) ground points excluded, (b) all points included. Leaf-off data: (c) ground points excluded, (d) all points included.

properties have an effect on the recorded discrete positions of laser pulse returns that create an ALS point cloud and that could be further linked to forest growth, disturbances, or phenology. However, there are also random effects related to the particular measurement configuration and possible systematic differences due to scanner settings and viewing angle (Keränen, Maltamo, & Packalen, 2016) between the compared datasets, but as Næsset (2009) and Wasser, Day, Chasmer, and Taylor (2013) concluded, the changes are more pronounced in the lower canopy layers. In addition to the flight configurations, the automatic gain control (AGC) influences the number of emitted photons and therefore the distribution of echoes (Vain, Yu, Kaasalainen, & Hyyppä, 2010), and can influence results when comparing the point cloud metrics from repeated ALS measurements.

CC_{ALS} as a proxy for canopy cover estimate depends on the number of returns per pulse, which can be a function of canopy structure and scanner settings. For our study, the first-to-all-echoes ratio did not significantly change for different datasets of leaf-on and leaf-off and was similar for different flying altitudes and different footprint sizes in leaf-on data, which corresponds to the findings by Næsset (2009). The first-to-all-echoes ratio in our dataset was slightly greater for the lower pulse repetition frequency compared to Næsset (2009), but that could be related to different scanners. CC_{ALS} estimates from ALS point clouds were significantly influenced by commercial thinning, as found in other studies (Ellis et al., 2016; Hevia et al., 2016). In our study, the CC_{ALS} decreased due to thinning by approximately 20% in leaf-on and leaf-off conditions. The species composition had no influence on CC_{ALS} change using leaf-on data but was relevant for leaf-off conditions. This is most likely due to the difference in the phenological stages in our leaf-off data acquisition times from 2009 and 2013. The somewhat large interquartile range of CC_{ALS} difference in the reference stands is most likely the cause of the CC_{ALS} estimation error, as was shown by Arumäe and Lang (2018), and for leaf-off data, the phenological differences also add up to the estimation errors. Similar to Arumäe and Lang (2018), raising the threshold up to 8 m systematically decreased the CC_{ALS} values using both leaf-on and leaf-off data, but provided no advantage in thinning detection.

The changes in ALS point cloud height distribution skewness, kurtosis, canopy relief ratio, and mode were not sensitive to the thinning cuttings. The point cloud height distribution percentiles did not decrease as would have been expected, opposite to findings by Nijland et al. (2015), who concluded that the range between H_{P95} and mean height estimate decreases with an increase in thinning grade in boreal forests. In our results, there was no significant difference in the distance between H_{P50} and H_{P95} before and after thinning. We observed a systematic increase in H_{Px} over the four-year period of ALS measurements, which reflected the forest height increment and partly also an effect of the stand mean height increase when smaller trees are removed (Lang, Arumäe, Laarmann & Kiviste, 2017). In our dataset, the recovery time for the forest understorey ranged from one to four years with respect to the last ALS measurements, and the height percentiles were calculated excluding the near-ground points. If the forest understorey is sparse, then the median and upper H_{Px} are influenced only by the upper layer of trees, as the returns either occur from the upper part of the canopy or are excluded by the minimum height filter. In this situation, the distance between H_{P50} and H_{P95} would not change much after thinning. Nijland et al. (2015) used measurements where the time gap from thinning to ALS data was 10 years, which meant there was also enough time for the understory vegetation to recover and therefore become "visible" to the ALS.

The H_{Px} increment was greater in younger stands compared to older forests, and this difference was similarly present in both the leaf-off and leaf-on datasets, although the H_{Px} values in the leaf-off dataset were systematically lower. This finding agrees well with existing knowledge of forest growth in Estonia (Kängsepp, Kangur, & Kiviste, 2015; Metslaid et al., 2011). We also found a smaller height increment estimate for the reference stands compared to the stands that were thinned, which can be explained by higher soil fertility in the sample of thinned stands. The mean height increment over the four-year period was statistically significant and could be further used for site index estimates, which have been shown by Kandare, Ørka, Dalponte, Næsset, and Gobakken (2017) to be predictable based on just tree height. However, site index estimates using bitemporal ALS data (Noordermeer, Bollandsås, Gobakken, & Næsset, 2018) will also be influenced by thinning cuttings. We found a characteristic pattern in the H_{P80} increment, depending on the time of thinning relative to the repeated ALS measurements. The H_{P80} increments of stands thinned before the first ALS flight were dependent not on thinning year but on the site fertility index H_{100} and stand age at thinning, which corresponds to the common knowledge of forest management practice – younger stands, or stands growing in fertile site types, have greater height increment. Initially, the height increment for the dominant and codominant tree layers is known to decrease for a couple of years after thinning, before then starting to increase (Sharma, Smith, Burkhart, & Amateis, 2006). However, our data showed a greater increment for H_{P80} in the stands with thinning year closer to the latter ALS measurement. The contradiction can be explained by the recovery of the forest canopy after thinning, and interaction with the laser pulses in a measurement configuration characterized by relatively large footprints and sparse point cloud. The tree crowns in dense forests before thinning are short, narrow, and sparse due to competition. With the increased amount of nutrients, growth space, and light for single trees, more branches at the live crown base survive, branches grow longer, and crown diameter increases as a result. At the same time, crowns become opaquer because the foliage mass of each tree is increased, and this increased photosynthetic capacity is expressed by the increased growth of breast height diameter and height of trees. With narrower, shorter, and sparser tree crowns, the probability is greater for a laser pulse to penetrate the canopy. Therefore, pulse returns are triggered either from the upper part of tree crowns or from the ground.

As time passes since thinning, tree crowns grow wider and denser and the probability of returns at the live crown base level increases. Assuming that the reflectance of branches in the NIR spectral region does not change much after thinning, the probability of a pulse return is proportional to the area of crown projection at the selected canopy height. The increase in crown projection area as branches grow is proportional to the crown radius, which is greater at the lower part of tree crowns in hemi-boreal forests. This also decreases H_{P80} of sparse point clouds. The combination of the smaller footprint in the earlier measurement and larger footprint in the later measurement may have an influence in a random direction for each stand, due to the AGC being turned on during the ALS measurements.

In addition to the tree canopy recovery, the selection of points for calculation of the point cloud height distribution percentiles has a substantial effect on the change of the percentile values in stands thinned between the two ALS measurements. If ground returns are included, then the increment of H_{P80} in stands thinned between the two ALS measurements is less compared to that of stands thinned before the first or after the second measurement. The difference in point cloud height metrics when calculated first without ground points and then with ground points included may give additional information towards the assessment of changes in forest canopy structure, and for site index estimation.

High altitude flights are more cost-effective as a larger territory is covered from each flight trajectory, but it comes with the loss of point cloud density per unit area. However, such cost-effective bitemporal low-density ALS data have still the potential for applications in National Forest Inventories for the monitoring of increment and felling volumes. There are also possibilities for large forest owners and forest management companies to use such data to monitor forest regeneration and for detecting natural disturbances, which alter canopy structure similarly to commercial thinning.

Conclusion

The study showed that the bitemporal ALS measurements carried out after thinning do not indicate the disturbance, and there are no significant changes detectable in the chronosequence of thinned stands dependent on the time that has passed since the thinning event. However, the thinnings carried out between the two ALS data acquisitions were detectable, and differences between point clouds of ALS measurements were dependent on the time passed since the first ALS measurements.

The ALS point cloud height distribution metrics skewness, kurtosis, mode, and canopy relief ratio were insensitive to thinning; instead, CC_{ALS} was the most informative ALS metric for detecting thinning-like disturbances.

While CC_{ALS} decreased after thinnings, the point cloud height percentiles remained at the same value or increased. Increase in point cloud height percentiles was similar for both thinned and reference stands similarly, using either leaf-off or leaf-on data. The fitted linear models for ΔH_{P80} were also in good agreement with the known patterns of forest stand growth. Also, the height increment estimate and changes in CC_{ALS} were not influenced by the stand-dominating species; it was only relevant when using leaf-off ALS data, which is related to differences in phenophases during ALS measurements. The inclusion of ground returns in the calculation of ΔH_{Px} decreases the change in stands thinned between the two ALS measurements, and can be used as an additional information source.

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Geolocation

Aegviidu test site is located in Estonia, 59º 19′ 20” N, 25º 35′ 36” E.

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