Estimating vertical canopy cover with terrestrial and airborne laser scanning

LAURI KORHONEN*†, HARRI KAARTINEN‡, ANTERO KUKKO‡, SVEIN SOLBERG§ and RASMUS ASTRUP§

† University of Eastern Finland, School of Forest Sciences, P.O Box 111, FI-80101 Joensuu, Finland
‡Finnish Geodetic Institute, Geodeetinrinne 2, P.O. Box 15, FI-02431 Masala, Finland
§Norwegian Forest and Landscape Institute, P.O. Box 115, N-1431 Ås, Norway

Forest canopy cover (CC) is an important ecological variable and also a basis for the international definition of forest. CC is defined as the proportion of forest floor covered by the vertical projection of the tree crowns, i.e. unbiased CC measurements should be made using vertical observations. Only gaps between the crowns should be considered. If instruments having a non-zero angle of view are used to map the canopy, sides of the crowns will also be observed, which leads to overestimation of CC. Both airborne (ALS) and terrestrial (TLS) scanning lasers measure the canopy with non-vertical laser beams, i.e. CC estimates are likely to be biased.

We measured CC at 16 plots located in Eastern Finland and Southern Norway with a sighting tube to obtain an unbiased field CC, and compared these results to ALS and TLS-based estimates. In case of ALS, the simple proportion of single and first canopy echoes estimated CC very well with a small overestimation (absolute RMSE 3.7–7.6%, absolute bias -3.4–-4.4%) due to relatively narrow nadir angle. The TLS scanners used phase comparison method and had a hemispherical field of view, so instead of trying to calculate the proportion of canopy echoes, we used the points above the height threshold (1.3 m) to create a raster map of the canopy. In the initial image, the brightness of the 4-cm pixel was related to the number of echoes at the pixel. The image was first median filtered, then processed with morphological operations to reduce noise and remove within-crown gaps, and finally binarized to separate covered and open pixels. CC was then estimated as the proportion of canopy pixels. Although TLS created a detailed canopy map close to scanning points, just a small number of echoes were received from more distant crowns, which led to underestimation of CC by 42%–0.1% (absolute RMSE 8.0–17.9%, absolute bias 6.8–13.1%). We conclude that ALS can be safely used in CC estimation despite a minor bias. TLS allows detailed canopy mapping, but a dense network of scan points is required to cover the entire plot.

*Corresponding author. Email address: lauri.korhonen@uef.fi

1. Introduction

Forest canopy cover (CC), defined as the vertical projection of tree crowns ignoring within-crown gaps (Jennings *et al.* 1999, Gschwantner *et al.* 2009), is a forest characteristic that has recently become important in forest inventories. It is commonly used as an ecological indicator (Jennings *et al.* 1999, Gill *et al.* 2000) and also forms a basis for the international definition of forest (FAO 2000). However, its reliable estimation in the field using traditional methods is usually either too laborious or too inaccurate (Korhonen *et al.* 2006). Airborne (ALS) and terrestrial (TLS) laser scanning offer an effective and precise alternative for measuring the percentage of canopy gaps (Lovell *et al.* 2003, Danson *et al.* 2007, Solberg *et al.* 2009), and thus have a great potential to replace the less accurate field methods that are currently used in forest inventories (Korhonen *et al.* 2006).

The traditional methods for *in situ* canopy cover measurements include ocular estimates, sighting tubes (Rautiainen et al. 2005), spherical densiometers (Lemmon 1956), canopy photography (Korhonen and Heikkinen 2009), and modelling based on stem dimensions (Gill *et al.* 2000). Of these methods, the use of vertically balanced sighting tubes to estimate the proportion ground that is covered by the canopy is usually considered to give an accurate estimate of CC (Rautiainen *et al.* 2005). In practice, sampling transects are established so that they cover the entire plot. The measurer walks the lines and at each grid point looks upwards through the tube to determine whether the point is under a crown or not. Because such measurements require plenty of time, cameras or other instruments with non-zero angle of view are often used to reduce the number of sampling points. However, measuring a larger area from each point makes the estimated CC biased, because the sides of the crowns are also observed (Jennings *et al.* 1999, Paletto and Tosi 2009). When large view angles are used, the trees seem to fall towards the centre of the observed area, and CC is overestimated. This bias increases along with the angle of view, becoming significant at around 40° (20° from zenith) (Korhonen and Heikkinen 2009).

Airborne laser scanning provides data that is very similar to the dot counts with the sighting tube: all that is needed is to calculate the proportion of first and single echoes that are above a specified height threshold (i.e. canopy echoes) (Holmgren *et al.* 2008). The main difference is that the beams of a scanning laser are not exactly vertical (except at nadir), so it is likely that this method overestimates CC similarly to field measurements with non-zero angle of view. However, in typical ALS surveys the off-nadir angles are at maximum 20°, so this effect should remain relatively small. In addition, however, the penetration ability of an ALS pulse may be limited through small canopy gaps, and vary somewhat with the technical acquisition settings.

The potential of terrestrial lasers in mapping canopy gaps and density has also been demonstrated (Danson *et al.* 2007, Huang and Pretzsch 2010). Many TLS systems have hemispherical field of view, so CC estimated as the proportion of canopy gaps within the entire hemisphere will overestimate CC considerably. However, allocating the canopy echoes to a grid based on their XY coordinates should reduce this effect. Our aim in this study is to compare ALS and TLS-based estimates of vertical CC to accurate field data.

2. Materials

Our first study site is the Koli National park in Eastern Finland (63˚04´ N, 29˚51´ E). Seven 30 x 30 metre sample plots were scanned with both terrestrial and airborne lasers. All plots were located at Scots pine (*Pinus sylvestris* L.) dominated stands (Table 1). More fertile plots (16 and 17) also had a significant number of other species, mainly birches (*Betula spp.* L.) and higher understory vegetation. The rest of the plots were barren pine stands with very low understory vegetation. CC was measured using a sighting tube to determine if the sample point was covered or open. The density of the dot count grid was 1 x 2.5-metres, resulting in 403 points per plot. The methodology was similar to Korhonen *et al.* (2006), except that vegetation lower than 1.3 metres was ignored. Also typical forest parameters were recorded.

Table 1. Koli plot data.

Plot-ID	SP	CC	G	DgM	HgM	CBHgM
16	Pine 69%	80.9	25.8	31.4	23.7	11.0
17	Pine 58%	78.2	24.3	33.2	22.0	10.5
19	Pine 93%	63.0	22.4	23.9	18.4	11.3
20	Pine 99%	43.2	18.4	24.8	18.2	11.5
25	Pine 96%	66.5	29.3	31.2	24.4	12.1
26	Pine 98%	59.8	24.5	29.2	24.2	12.6
27	Pine 98%	59.3	22.9	23.8	18.5	13.3

Abbreviations: SP, dominant species; CC, canopy cover (%); G, basal area (m^2/ha), DgM, mean diameter at breast height (cm); HgM, mean height (m); CBHgM, mean crown base height (m). The mean values are given for the basal area median tree.

The Koli ALS data were obtained in July 2005, while other measurements were made during May– June 2006. Optech ALTM 3100 scanner (Optech Inc., Vaughan, Ontario, Canada) was flown at one kilometres altitude. Half scan angle was 11°, footprint size 25 cm, and mean pulse density 4.6 m^{-1}.

The Koli TLS data were acquired using a FARO LS 880HE80 scanner in June 2006. It is a continuous wave, 785 nm scanner, which uses phase modulation technique (Petrie and Toth 2009, p. 18) for distance measurement with three different carrier wavelengths and has an unambiguity range of approximately 76 m. Point measurement frequency was 120000 points per sec, vertical field of view 320° and horizontal field of view 360°. Beam size was 3 mm at exit and beam divergence was 0.25 mrad (0.014°). Distance measurement error was 3 mm at 25 m (84% reflectivity). Five to eight scans were made in each plot. Same measurement resolution was used for all scans, producing a point spacing of 6 mm at the distance of 10 m. Individual scans were georeferenced to local coordinate system using spherical reference targets. Coordinates for the reference targets were measured using a Trimble 5602 DR 200+ total station, which was setup using the known coordinates of the rectangle-shaped test plot corners. Because the data was meant for timber volume studies, scan points were selected subjectively so that the stems could be viewed from several directions. Thus many scan points were located near the edges of the plot, which was not ideal for CC estimation.

The second study site is located in Lardal, Southern Norway (59˚23´ N, 9˚58´ E). The stands were fertile mixed forests, usually dominated by Norway spruce (*Picea abies* (L.) Karst). Circular sample plots with 12.5 metres radius were measured during summer 2009. CC measurements were made similarly to Koli, resulting in 195 sample points per plot. The ALS data were gathered with the Optech ALTM05SEN180 and ALTM04SEN161 scanners, 690 m above ground. Half scan angle was 12°, footprint size 13 cm, and mean pulse density 10.0 m^{-1}. Four TLS scans were achieved from six of the Lardal plots. One scan was taken at the plot centre while the other three were obtained at six metres distance (N, SE, and SW). Otherwise the setup was similar to Koli.

Table 2. Lardal plot data.

Plot-ID	SP	CC	G	DgM	HgM	CBHgM
3664_2	Spruce 93%	76.9	40.8	29.0	21.9	10.0
3684_7	Spruce 98%	84.1	45.5	30.9	18.9	5.7
3721_5	Spruce 100%	87.2	48.9	31.4	23.7	9.1
3726_1	Spruce 91%	79	42.3	25.7	19.2	6.7
3731_12	Spruce 88%	82.6	41.5	27.3	22.0	4.8
4373_3	Birch 37%	63.6	14.6	32.5	18.3	2.3
4373_6	Spruce 98%	76.9	27.3	22.1	19.1	8.9
4375_3	Spruce 99%	73.8	33	25.9	25.8	10.1
4375_5	Spruce 73%	88.7	45.2	29.1	25.8	8.1

Abbreviations: SP, dominant species; CC, canopy cover (%); G, basal area (m^2/ha), DgM, mean diameter at breast height (cm); HgM, mean height (m); CBHgM, mean crown base height (m). The mean values are given for the basal area median tree.

3. Methods

The ALS data from both sites were processed similarly: the height of the echoes above the digital terrain model was calculated and the percentage of first and single echoes that were above a 1.3 metres threshold was used as the CC estimate. In addition, the high density ALS data were decimated to a density of 1 pulse per m^2, which is typical to practical forest inventories. This was done using a grid-based method similar to Vauhkonen *et al.* (2009), and CC was re-estimated using the decimated data.

Processing of the TLS data involved several steps. The scanners used the phase comparison method, and therefore the analysis was different from earlier studies in which time-of-flight scanners have been utilized (Danson et al. 2007, Huang and Pretzsch 2010). First, the scanners' own software was used to filter most of the noise and create georeferenced images depicting the density of points above 1.3 m (Fig. 1). Image resolution was 4 cm and (8-bit) image brightness was scaled according to the point density within the cell. After georeferencing, the scanned point clouds were filtered to reduce the amount of outlier points, which occur in phase-based measuring system when the measuring beam hits more than one target or no target at all. Filtering was done by removing all points that had a greater distance than 20 cm to half of its 3 by 3 neighbouring points in scanner's row-column system. Also all dark points, i.e. points with low returning intensity, were removed. FARO Scene software was used for point cloud georeferencing and filtering.

All ground points were deleted and point clouds were processed to create a map of the canopy. Here the analysis differed slightly between Koli and Lardal plots. For the Koli plots, this was done by applying the 'Clear view mode' directly in Scene software: it adds transparency to the otherwise completely opaque point cloud rendering. This allows for viewing through very dense point clouds and gives a better impression of the spatial structure of the underlying point cloud. Settings for the clear view mode and laser point size were selected so that the orthogonal top view of the 3D-point cloud was visually optimized. Image crops were taken and image corner coordinates and pixel size were determined using test plot corner coordinates and ArcGIS-software. Lardal TLS data were pre-processed by the contractor (Treemetrics Ltd., Cork, Ireland) and the point cloud was delivered in ASCII format. This time the Scene software was not available, so instead the raw number of above-ground echoes was calculated for each cell. Because the echo numbers were very high in some places (especially at the stems) and low elsewhere, the echo counts were log-transformed to reduce the intensity range of the images. In this way the Lardal canopy images became comparable to the Koli canopy images.

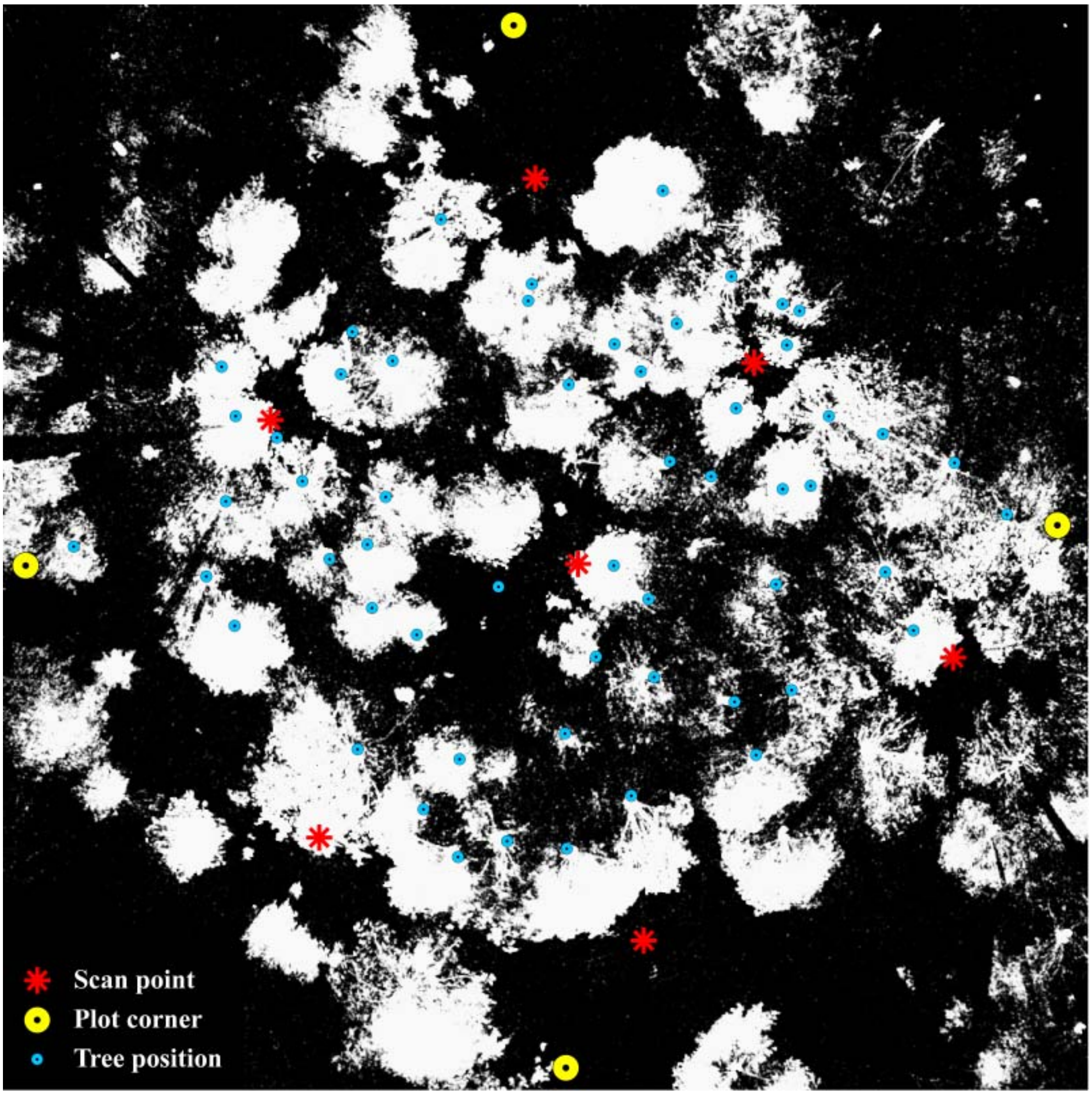

Figure 1. TLS-based canopy map from Koli plot 25 was made with FARO Scene software and imported to ArcGIS for visualization. Tree positions come from field measurements.

These images were analysed further using MATLAB® 7.9.0 numerical computing environment and programming language (MathWorks Inc. 2010) and image processing toolbox extension. The processing chain was as follows:

1. Median filtering to reduce noise, repeated twice.
2. Removal of remaining small peaks and gaps with mathematical greyscale morphology (Soille 2003; see also Wikipedia title on mathematical morphology). Bright peaks were smoothed by morphological reconstruction (Vincent 1993): the image was first eroded, and the eroded image was used as marker and the median filtered image as a mask in Matlab's function *imreconstruct*. Gaps were removed similarly by using the negative of the resultant image.

3. Binarization to separate canopy and empty pixels. Threshold values were selected so that the crowns could be separated as well as possible. In Koli the 8-bit brightness limit was 25 DN. With log-transformed Lardal images the limit was 2.1, corresponding to eight individual echoes.
4. CC was calculated as the percentage of canopy pixels of all pixels that were inside the plot.

The final maps (Fig. 2) were generalized versions of the initial maps (e.g. Fig 1.) where processing had eliminated small within-crown gaps, so that CC estimated from the map was equivalent to the estimates obtained with the sighting tube. In addition, most irrelevant details between the continuous canopy areas were removed in the process.

The accuracy of the results was examined by calculating root mean squared error (RMSE) and bias between the estimates (ŷ) and field reference (y) (Eqs. 1–2).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \qquad \text{(Eq. 1)}$$

$$Bias = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \qquad \text{(Eq. 2)}$$

4. Results

A general view of the quality of our data can be obtained from Fig. 2, where ALS canopy hits and TLS-based canopy map are compared. The ALS point cloud clearly shows where the crowns are, and the TLS map has a good agreement with the ALS results near the scan points. However, the TLS map has large shadowed areas especially outside the plot borders, but also between the scan points. There echoes were often received only from the stem and lowest braches, while most of the crown stayed hidden. In addition, parts of the canopy were shadowed by nearby stems, leaving black strips into otherwise continuous canopy (Fig. 1).

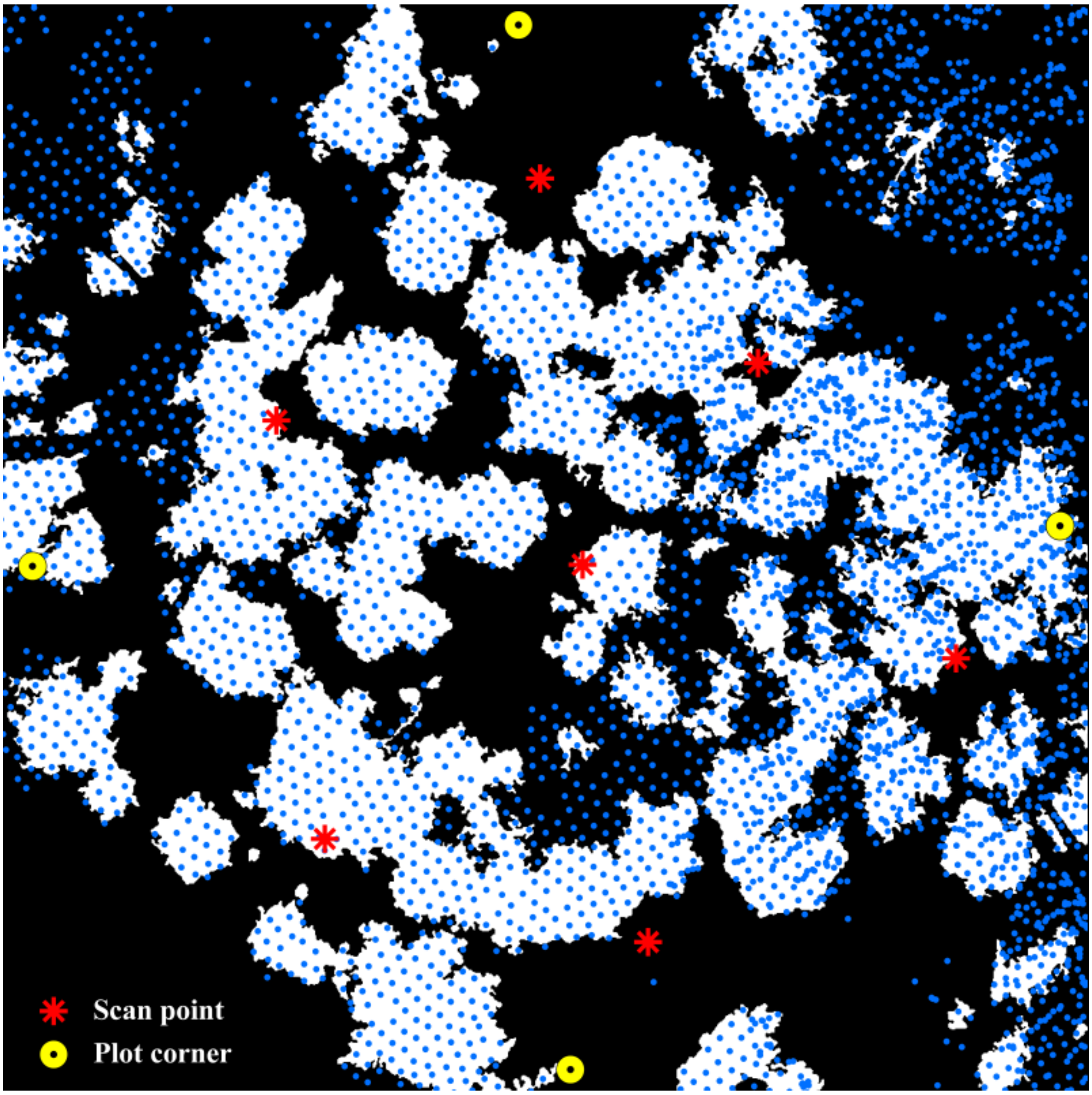

Figure 2. TLS-based binary canopy map from plot 25 overlaid by ALS vegetation hits. Some of the crowns visible in ALS point cloud were poorly detected by the TLS.

Table 3. Koli results.

Plot	CC	TLS scans	TLS-CC	ALS-CC	Decimated ALS-CC
16	80.9	8	75.6	82.6	80.0
17	78.2	8	66.4	82.7	80.9
19	63.0	6	54.2	65.5	62.5
20	43.2	6	32.7	44.0	40.5
25	66.5	7	54.1	72.3	68.9
26	59.8	5	18.0	63.9	61.4
27	59.3	7	58.0	63.5	57.1

Table 4. Lardal results.

Plot	CC	TLS scans	TLS-CC	ALS-CC	Decimated ALS-CC
3664_2	76.9			82.5	80.4
3684_7	84.1	4	77.9	89.0	85.9
3721_5	87.2	4	87.1	91.6	91.5
3726_1	79.0	4	72.7	80.2	83.3
3731_12	82.6	4	76.8	88.5	87.1
4373_3†	63.6			76.7	74.3
4373_6†	76.9	4	62.4	88.8	85.1
4375_3	73.8	4	65.8	75.9	79.0
4375_5†	88.7			79.1	73.3

†Field CC measured by different person.

The comparison of the results with the field-measured CC confirmed what could be seen visually from the images (Tables 3 and 4). At Koli, raw ALS results were very close to sighting tube estimates (RMSE 3.7%, bias -3.4%), and when the data were decimated to typical inventory density, the two methods yielded an even higher agreement (RMSE 2.0%, bias -0.1%). In Lardal the ALS and field inventory results did not agree as much as in Koli (RMSE 7.6%, bias -4.4%). Still, however, the general view was very similar – ALS overestimated field-measured CC by a few percent. One thing to be noted was that if three Lardal plots where field-CC was measured by a less experienced field-worker were removed from the analysis, RMSE decreased to 4.4%. The bias, however, remained the same due to removal of an outlier plot (no. 4375_5), where ALS underestimated field-CC. The point cloud decimation reduced the bias from -4.4 to -3.0%, i.e. it did not reduce the bias as much as with the less dense Koli data.

The TLS results were opposite to ALS: CC was always underestimated. In Koli RMSE and bias were 17.9% and 13.1%, respectively, and in Lardal 8.0% and 6.8%, respectively. This result is in line with the visual observation that more distant crowns remained shadowed in the TLS maps. This problem was especially evident at Koli plot 26, where field CC was 63.9% but TLS estimate only 18.0%. One reason for this unacceptable error was that only five scans were made, four of which were from the corners, which was not enough to cover the entire plot.

5. Discussion

Our results indicate that a simple ALS-based vegetation index can produce accurate canopy cover data, at least if the scan angle is kept small. The results also improved when the data density was reduced to approximately one pulse per square meter. The slight overestimation of CC may be explained by the shadowing effect, i.e. when pulses are arriving at an angle then their probability of having a first or single echo at the ground is lower as compared to vertical pulses. Grid-based decimation of the ALS data reduced the bias. Most likely this resulted from the decimation procedure being most pronounced in the crowns where the density of echoes are high, leaving a relatively higher share of ground-echoes in the remaining data set. ALS data seems to be the best available solution for acquisition of reliable canopy cover data for large areas. As ALS is increasingly used in practical forest inventories due to its ability to produce high-precision estimates on growing stock, the availability of data for CC estimation should also increase.

TLS-based canopy mapping also produced accurate maps of the canopy near the scan locations, but crowns further away remained occluded. Thus TLS is better suited for mapping canopy gaps in the hemispherical perspective projection than vertical map projection. However, in small plots where several scans are made, and in open canopies with good visibility, TLS can produce a very accurate description of the horizontal and vertical structure of the canopy. The methods used to generate the canopy maps functioned very well and can be used safely if such maps are required. However, in cases where a simple estimate of CC is enough and TLS measurements are not otherwise available, traditional field techniques such as sighting tubes or point-and-shoot canopy photography may be more convenient alternatives.

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