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Airborne laser scanner (LiDAR) proxies for understory light conditions

Cici Alexander [a,b,*], Jesper Erenskjold Moeslund [a,b,c], Peder Klith Bøcher [a,b], Lars Arge [b], Jens-Christian Svenning [a]

[a] Ecoinformatics & Biodiversity Group, Department of Bioscience, Aarhus University, Ny Munkegade 114, DK-8000 Aarhus C, Denmark
[b] Center for Massive Data Algorithmics (MADALGO), Department of Computer Science, Aarhus University, IT-parken, Aabogade 34, DK-8200 Aarhus N, Denmark
[c] Agricultural Systems and Sustainability, Department of Agroecology, Aarhus University, Blichers Allé 20, DK-8830 Tjele, Denmark

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ABSTRACT

Canopy cover and canopy closure are two closely related measures of vegetation structure. They are used for estimating understory light conditions and their influence on a broad range of biological components in forest ecosystems, from the demography and population dynamics of individual species to community structure. Angular canopy closure is more closely related to the direct and indirect light experienced by a plant or an animal than vertical canopy cover, but more challenging to estimate. We used airborne laser scanner (ALS) data to estimate canopy cover for 210 5-m radius vegetation plots in semi-open habitats and forests in protected nature areas in Denmark. The method was based on the area of Thiessen (Voronoi) polygons generated from the ALS points. We also estimated angular canopy closure by transforming ALS points from Cartesian to spherical coordinates, and calculating the percentage of azimuth and zenith angle intervals which contained points. We compared these estimates with field-based estimates using densiometer for 60 vegetation plots in forest. Finally, we compared ALS-based estimates of canopy cover and canopy closure to field-based estimates of understory light, based on the average Ellenberg indicator values for light for the plant species present in a given plot. The correlations of Ellenberg values with ALS-based canopy closure were higher (r^2: 0.47) than those with ALS-based canopy cover (r^2: 0.26) and densiometer readings (r^2: 0.41) for the forest sites. ALS-based canopy closure is thus a reasonable indicator of understory light availability and has the advantage over field-based methods that it can be rapidly estimated for extensive areas.

1. Introduction

Understory light conditions within a forest are determined by a number of factors, with the structure of the tree canopy being particularly important (Jennings et al., 1999). The quantity, quality, and spatio-temporal distribution of light near the forest floor are primarily controlled by the structure of the canopy, which influence a broad range of biological components in forest ecosystems, from the demography and population dynamics of individual species (Svenning, 2002; Svenning & Magård, 1999) over species distributions (Svenning, 2000) to community structure (Frelich et al., 2003). Plants differ in their requirement for light, with some plants preferring to grow in shade, others in full sunlight, and yet others in intermediate conditions (Ellenberg, 1988). The forest canopy is often manipulated for creating conditions favourable for the survival and growth of certain tree species of commercial or, more rarely, of conservation value (Frelich et al., 2003). Both ecologists and foresters are therefore interested in mapping forest understory light conditions (Jennings et al., 1999).

Canopy cover and canopy closure are two closely related measures which are useful for estimating the microclimate and light conditions at the forest floor. These measures are also useful for assessing habitat suitability for different plants and animals, and for estimating functional variables such as Leaf Area Index (LAI). Canopy cover is the proportion of the forest floor covered by the vertical projection of tree crowns, and is often estimated in the field using transects and vertical sighting tubes. Canopy closure is the proportion of the sky obscured by vegetation when viewed from a single point, and is estimated from hemispherical photographs or using spherical densiometer (Jennings et al., 1999; Korhonen et al., 2006, 2011).

Canopy closure should provide a better description of the light conditions under a canopy than canopy cover as all the directions in which light reaches a point below the canopy are taken into consideration (Jennings et al., 1999). Hemispherical photographs are often used for estimating canopy gap fraction, the fraction of the sky visible from a point below the canopy, which is a complementary measure to canopy closure. Canopy gap fraction can be used to determine leaf area index (LAI), defined as the one-sided green leaf area per unit ground area in broadleaved canopies, or as the projected needle-leaved area per unit ground area in needle canopies (Law et al., 2008). The sky (light) and canopy (dark) pixels in a grey-scale hemispherical image are classified based on a threshold, which is dependent on sky

* Corresponding author at: Ecoinformatics & Biodiversity Group, Department of Bioscience, Aarhus University, Ny Munkegade 114, DK-8000 Aarhus C, Denmark. Tel.: +45 87 15 61 28; fax: +45 87 15 43 26.
E-mail address: cici.alexander@gmail.com (C. Alexander).

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conditions. Hemispherical photographs should be taken under uniform sky lighting either early or late in the day, or under overcast conditions, as sun glare may lead to overestimation of canopy gaps (Steele-Feldman et al., 2006).

Terrestrial laser scanners (TLS) have been used to estimate canopy gap fraction, providing results comparable to those from hemispherical photographs (Danson et al., 2007; Seidel et al., 2012). TLS have the advantage that they also provide additional information about the vertical structure of vegetation. Estimates of canopy gap fraction using a TLS are usually obtained from two orthogonal vertical scans (Danson et al., 2007), and the precision is high, especially in the areas where the scans overlap. However, field-based methods for the estimation of canopy cover or closure are time-consuming. Remote sensing could provide a method for large-scale mapping of canopy cover and closure, if these estimates could be validated by comparing them to field-based measurements (Fiala et al., 2006; Korhonen et al., 2011).

Airborne laser scanners (ALS) use light detection and ranging (LiDAR) to obtain geo-referenced points on and above the terrain. A few studies have explored the use of ALS in estimating canopy gap fraction and LAI. Riaño et al. (2004) found that the percentage of ALS points from the canopy had a high correlation with canopy gap fraction estimated from hemispherical photographs, and consequently also with LAI. The percentage of canopy hits were calculated within different radial distances from a point, and their results showed that the radius yielding the best estimates was influenced by canopy height. They additionally found differences between the estimates for deciduous and evergreen trees. Morsdorf et al. (2006) similarly considered different radial distances to compute canopy cover and LAI showing that radii of 2 m and 15 m provided the best results for canopy cover and LAI, respectively.

Most of the estimates of canopy cover from airborne laser scanner data are based on the proportion of echoes from vegetation above a certain height (Korhonen et al., 2011; Morsdorf et al., 2006), often referred to as fractional cover (Morsdorf et al., 2006). A method based on the number of points could overestimate canopy cover if laser scanning systems that collect multiple echoes are used in open forests, or there are variations in point density within an area due to overlapping flight strips. This problem could be addressed if surface area, rather than number of points, is used to estimate canopy cover. Areas of Thiessen polygons, also known as Voronoi or Dirichlet tessellations, generated from ALS points could be used to estimate canopy cover based on surface area.

There are inherent differences between estimates of the vertical distribution of foliage by airborne and terrestrial measurement techniques. The viewing directions of the two methods differ, with ALS looking downwards from above the canopy and terrestrial instruments looking upwards from the forest floor. Notably, the presence of tree trunks and branches in images affects estimates of LAI from hemispherical photographs, spherical densiometer and TLS (Seidel et al., 2012). For field-based instruments with an angular field of view, the observed volume is an upward facing cone. However, in previous studies concerning canopy closure the observed volume has been cylindrical (Solberg et al., 2009). The penetration of the canopy by ALS is dependent on sensor properties and flight settings, influencing point density, as well as the density of foliage. Even with these differences, if it is possible to derive an angular measure of canopy closure from ALS, it could provide a measure that is not influenced by sky conditions or the threshold used for binary classification, as is the case with hemispherical photography. It would be more representative of the upper part of the canopy than estimates from terrestrial instruments, and could cover large areas in much less time than field-based methods.

The extent to which ALS-derived canopy structure variables are good estimators of understory light availability may be evaluated by examining their correlation with the average Ellenberg indicator values for light (EIV_{light}) for plant species within understory vegetation plots (Diekmann, 1995; Dzwonko, 2001). Indicator values have been developed as estimates of the preferred light conditions for plants, first for Central Europe (Ellenberg, 1988) and later expanded to other regions, e.g., the British Isles (Hill et al., 1999). The Ellenberg indicator values range from 1 to 9, with 1 denoting species preferring deep shade and 9 denoting species preferring full sunlight (Ellenberg, 1988).

The overall aim of this study was to develop proxies for canopy cover and canopy closure based on discrete-return ALS data, and to evaluate whether these ALS-based canopy variables were correlated with understory light conditions as estimated from the understory vegetation by EIV_{light}. Our specific objectives were (1) to develop proxies for canopy cover and canopy closure based on ALS data, and (2) to determine whether there is a relationship between these ALS-based canopy structure proxies and EIV_{light}, predicting a stronger relationship for angular canopy closure than vertical canopy cover.

2. Study Area

A number of sites in Denmark are monitored through the National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environment (NOVANA), designed to monitor Danish habitats within the European NATURA 2000 network established under the Habitats Directive of the European Union, 1992. The study area includes seven NOVANA sites, which constitute three groups of sites (Fig. 1), each including both semi-open habitat and forest. The sites included the following NATURA 2000 habitat types: active raised bogs, alkaline fens, European dry heaths, species-rich *Nardus* grasslands on silicious substrates, old acidophilous oak woods with *Quercus robur* on sandy plains and other forests. There are 150 plots in open habitat and 60 plots in forest (Table 1). The sites together cover an area of 177 ha.

3. Field Datasets

Species occurrence data for vascular plants, bryophytes and lichens in the study area were collected under the NOVANA programme within 5-m radius plots in the open sites, and in 5- and 15-m radius plots in the forest sites. We used the species occurrence data collected in 2006, 2007 and 2009 (Table 1) for this study. The EIV_{light} for each of these species was selected as the modified values for Britain (Hill et al., 1999), whenever they were available, as these values are considered to be more appropriate for Denmark, and otherwise as the original values from Ellenberg (1988). The average EIV_{light} was calculated for the 5-m radius open-site and forest plots as well as the 15-m radius forest plots.

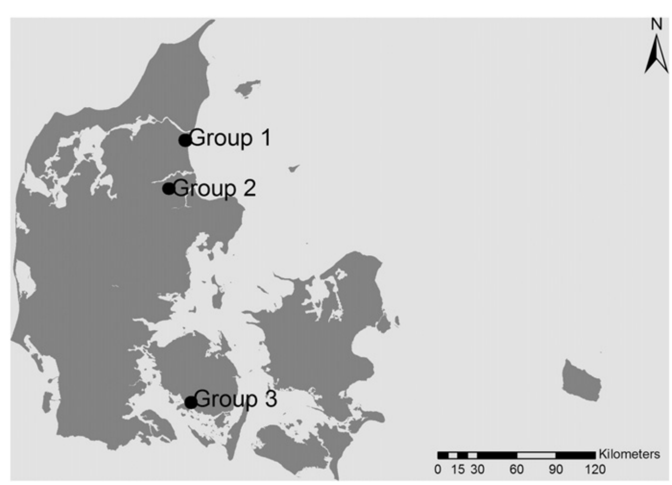

Fig. 1. Locations of the three groups of sites: (a) Site group 1 — sites 1105 and 3018, (b) 2 — sites 1298 and 3037 and (c) 3 — sites 1543, 1561 and 3084. The site numbers are those designated under the National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environment (NOVANA) programme.

Table 1
Information about the study sites and field data collection.

Grouped site ID	Site ID	Type	Number of plots	Field data collection
1	1105	Open	39	2007
	3018	Forest	20	2007
2	1298	Open	31	2009
	3037	Forest	20	2007
3	1543	Open	60	2006
	1561	Open	20	2006
	3084	Forest	20	2007

Canopy structure was recorded for the forest plots in the field using densiometers. The canopy variable measured using a densiometer is considered to be a hybrid of canopy cover and closure (Fiala et al., 2006). At viewing angles larger than 30° from the zenith, canopy cover may be overestimated (Bunnell & Vales, 1990; Jennings et al., 1999; Korhonen et al., 2006; Paletto & Tosi, 2009), with the measure being more related to canopy closure. Most spherical densiometers have 24 quarter-inch squares, with four equidistant dots within each square. The number of dots, out of 96, representing the canopy is converted to the percentage cover/closure by multiplying with 1.04 (Lemmon, 1956). Densiometer readings were recorded at four locations; 2 m to the North, East, South and West of the centre for the forest plots, and the average of these four values were calculated.

4. Processing of ALS Data

ALS data were collected in April and May 2006 by COWI (2007), an international engineering and planning company, using an Optech ALTM 3100 airborne laser scanner. The data were recorded at an altitude of 1.6 km with a footprint diameter of 50 cm at nadir (directly below the aircraft), with a 24° maximum off-nadir angle. The point density was approximately 1.5 m^{-2}, including the points from overlapping flight strips. Both the first and the last echoes were used in the reported analyses. Aerial images of the study areas were used for visual analysis.

Canopy cover based on Thiessen polygons were estimated for all the 5-m plots in open and forest sites. Canopy cover and closure were estimated for the 15-m forest plots. These ALS-based estimates were compared with field-collected densiometer data as well as vegetation-based understory light indicator values. The latter were computed based on plant species occurrence data for the vegetation plots, calculating non-abundance-weighted average EIV_{light} for each plot. Correlations between ALS-based canopy variables and average EIV_{light} were calculated. The analyses were performed in ArcMap 10.1 and MATLAB R2010b.

4.1. Pre-processing

Ground points in the ALS dataset were classified using the filtering algorithm based on Triangulated Irregular Network developed by Axelsson (2000) and implemented in the commercial software TerraScan (www.Terrascan.fi). A digital terrain model (DTM) at 2-m resolution was generated from these ground points using the SCALGO software (SCALGO, 2011) due to its ability to triangulate and rasterise large ALS datasets. The heights of all points from the DTM were calculated in ArcGIS.

4.2. Estimation of Canopy Cover from ALS Data

Thiessen polygons define the area of influence around each point, i.e., the area that is closest to each point relative to all other points in the dataset. They are the perpendicular bisectors of the edges of triangles from a Delaunay triangulation of the points (Burrough & McDonnell, 1998). Thiessen polygons were generated from the ALS points within all the plots. Canopy cover was estimated as the percentage of each plot covered by Thiessen polygons containing points 1 m or above from the ground. This was compared with an estimate of canopy cover based on the percentage of echoes at or above 1 m from the ground.

4.3. Estimation of Canopy Closure from ALS Data

Canopy closure was estimated for plots in the forest sites. Cartesian coordinates of the ALS points within a specified distance from the plot centres were converted to their spherical coordinates. The x, y and z coordinates of the points were thus converted to θ (theta), φ (phi) and R. Theta and phi are the angular displacements in radians measured from the positive x-axis and the x–y plane, or the azimuth and zenith angles, respectively. R is the distance from the origin, the centre of the plot at the ground level, to the point. Only points at or above 1 m from the ground were considered for estimating canopy closure.

ALS points within a horizontal distance of 2 m, 3 m, 5 m and every 5 m thereafter up to 100 m were selected for estimating canopy closure. Although these distances were often greater than the plot sizes, the trees in the surrounding area also influence the proportion of the sky obscured by vegetation, and so were included in the calculation. The zenith angle was converted to degrees and inversed – from 90° to 0° instead of 0° to 90° – so that a point at the zenith would appear in the middle of the circle, when the azimuth and elevation angles were plotted in MATLAB. This was done so that the plot would

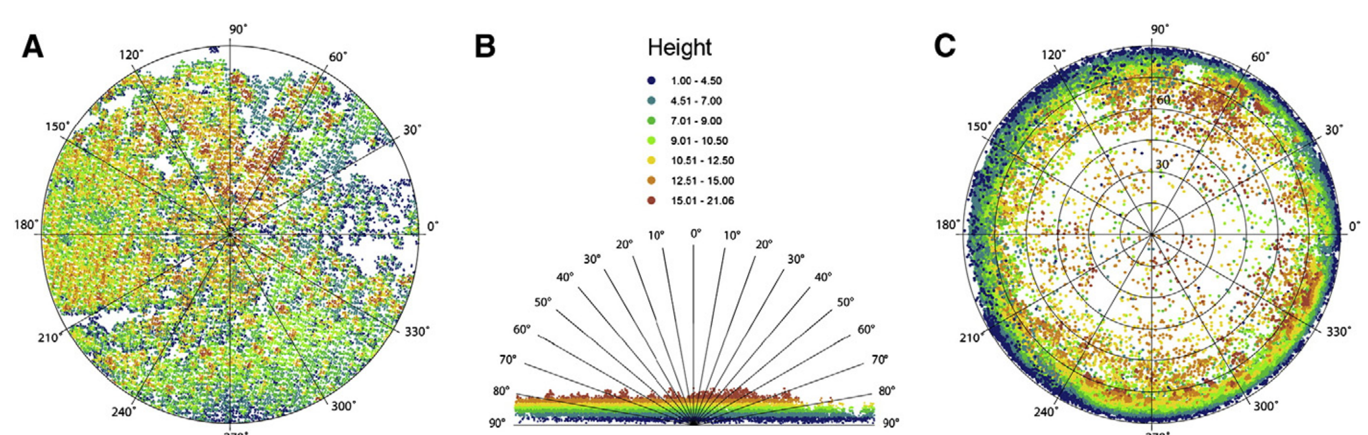

Fig. 2. (a) ALS points within 100 m of the centre, and at heights of 1 m or above from the ground in a sample plot (Site 3018 Plot 5), displayed by elevation; Points are displayed by their azimuth angle (θ) from the positive x-axis (A) and zenith angle (φ) from the positive z-axis (B) with the centre of the plot as the origin. (C) Points within the circular plot in the polar coordinate system with the azimuth angle as the angular coordinate and the zenith angle as the radial coordinate.

contain information similar to a hemispherical photograph, or a convex densiometer with a viewing angle of 180° (Fig. 2).

In the estimation of canopy closure from hemispherical photos, densiometer and TLS, the viewing angles from the zenith can be specified. This can also be done for the estimation using ALS data. However, the entire hemisphere was considered for this study since this provides the best estimates of canopy closure (Jennings et al., 1999). Canopy closure or gap fraction is estimated from a hemispherical photograph by computing the fraction of cells within specified radial and angular intervals. Similarly, the fraction of pyramidal elements within specified azimuth and zenith angle intervals that contain ALS points were computed for the ALS data. Zenith angle intervals of 1, 2, 3, 5, 10

Fig. 3. ALS points within 50-m radius of the plot centres, and above 1 m from the ground, are displayed as red dots. The average Ellenberg indicator values for light are also shown for (a) site groups 1 — sites 1105 and 3018, (b) 2 — sites 1298 and 3037, (c) 3 — sites 1543, 1561 and 3084.

c

Fig. 3 (*continued*).

and 15° were considered for the estimation. In addition to the above, 20, 30 and 45° were also considered for the azimuth angle intervals. Canopy closures for all the plot radii with all combinations of the azimuth and zenith angle intervals were calculated.

4.4. Comparison of ALS-based Canopy Variables with Field-based Estimates

The estimates of canopy cover and closure from ALS data were compared with the densiometer readings. From the ALS-based estimates of canopy closure, the values for the plot radius and the azimuth and zenith angle intervals with the strongest correlation with EIV_{light} were determined for all the sites as well as for each site separately. These estimates were used for the further analyses. The ALS-based estimates of canopy cover and closure and the field-based estimates were compared with the average EIV_{light} for both the 5-m and the 15-m plots.

5. Results

5.1. Canopy Cover from ALS Data

Thiessen polygon-estimated ALS-based canopy cover visually corresponded well with the aerial images for each site. It was highly correlated ($r = 0.99$) with the canopy cover estimate based on number of echoes. The estimate based on Thiessen polygons was used for all further analyses, since it has a stronger theoretical relation with the surface area of canopy than the number of points. The plant-based EIV_{light} generally was higher for the open sites than for the forest sites, and in most cases corresponded well with ALS-based canopy cover, with higher EIV_{light} at lower canopy cover (Fig. 3).

ALS-based canopy cover had a negative correlation with EIV_{light} for all the sites (overall $r = -0.72$), with stronger correlations when adjacent open and forest sites were grouped than when they were treated as separate sites. When all open sites and all forest sites were grouped together as two separate groups, the correlations were stronger for the open sites than for the forest sites (Table 2 and Fig. 4).

5.2. Canopy Closure from ALS Data

Canopy closure was estimated by plotting the ALS points around the centres of the forest plots in the polar coordinate system, with the azimuth angle as the angular coordinate and the zenith angle as the radial coordinate (Fig. 5).

The resolution of the pyramidal elements – azimuth and zenith angle intervals – used for calculating canopy closure had a large influence on the estimated canopy closure. The estimated angular canopy closure increased with increasing azimuth and zenith angle intervals (Fig. 6B & C). Overall, the correlation of canopy closure with EIV_{light} was the highest when the ALS points within 50 m of the plot centres were used, and canopy closure was estimated for azimuth angle intervals of 45° and zenith angle intervals of 1°. Canopy closure increased

Table 2
Pearson correlations between the ALS-based estimates of canopy cover, and the average Ellenberg indicator values for light for the 5-m plots ($p < 0.05$), and the root-mean-square-error (RMSE) from simple linear regression. The values for the open and forest sites, and the grouped sites are also shown.

	1105	3018	1298	3037	1543	1561	3084	Open Sites	Forest Sites
Cover5 – $EIV_{light}5$	−0.66	−0.47	−0.59	−0.64	−0.39	−0.68	−0.60	−0.63	−0.49
RMSE	0.31	0.50	0.11	0.37	0.30	0.28	0.54	0.35	0.65
Cover5 – $EIV_{light}5$		Site 1: −0.77		Site 2: −0.89			Site 3: −0.78		All Sites: −0.72
RMSE		0.39		0.35			0.39		0.5

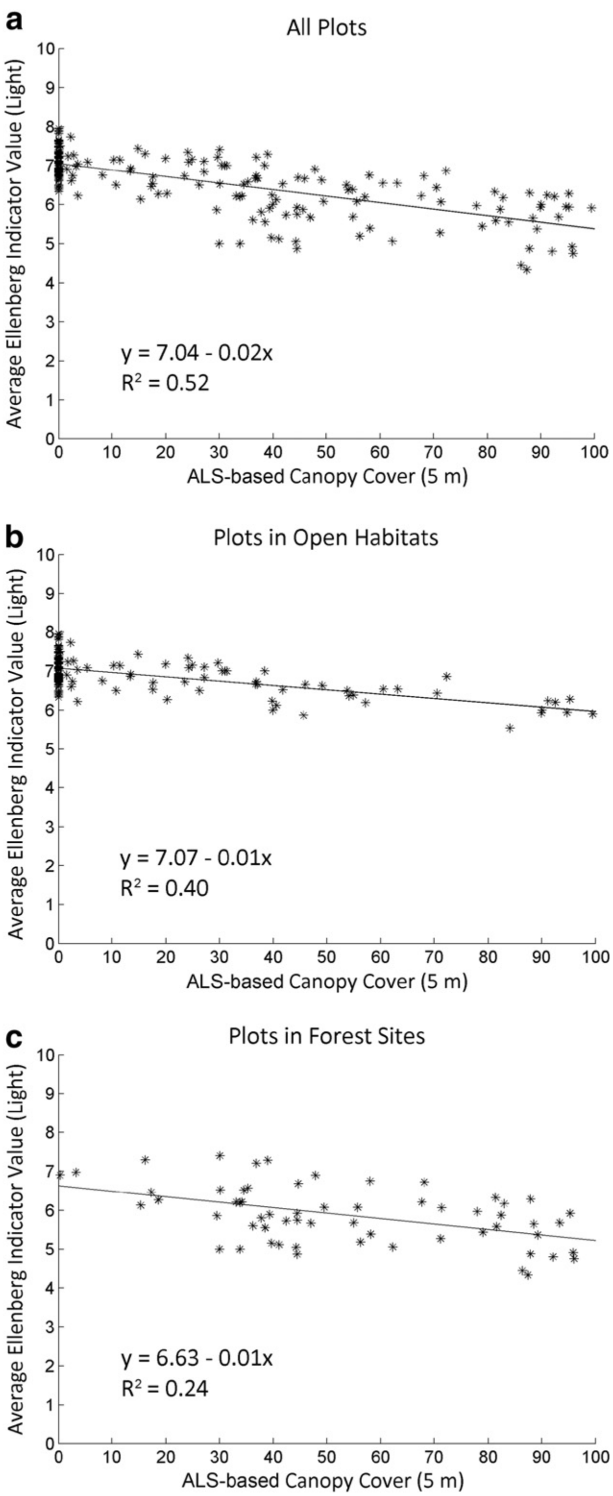

Fig. 4. Correlations between the ALS-based estimates of canopy cover and EIV_{light} for (a) all plots, (b) plots in open sites and (c) plots in forest sites.

with the radius of the plot up to a distance of approximately 50 m, and then remained more or less constant, for a particular azimuth and zenith angle interval (Fig. 6A).

There was much variation in the correlations of canopy closures with EIV_{light} with varying radial distances, azimuth and zenith angle intervals. There were also differences between the three sites and the overall values. The radial distances (d), and azimuth (a) and zenith (z) angle intervals yielding the highest correlations with EIV_{light} for the forest plots also varied between sites: Site 3018 (d: 45, a: 2, z: 10); Site 3037 (d: 5, a: 10, z: 5); Site 3084 (d: 40, a: 1, z: 5). Increasing the radial distance beyond 50 m did not increase the correlation with EIV_{light} for the individual sites.

5.3. Correlations Between Canopy Variables and Indicators of Understory Light Conditions in Forest Plots

Overall, the correlation between ALS-based canopy closure and EIV_{light} for the forest plots was higher ($r = -0.69$) than the correlations between ALS-based canopy cover and EIV_{light}. Although, ALS-based canopy cover and closure are correlated, densiometer readings have a higher correlation with canopy closure than canopy cover (Fig. 7 & Table 3).

The estimates from densiometer readings showed a higher correlation ($r = 0.76$) with canopy closure when only the ALS points within an angle of 40° from the zenith were included in the calculation for site 3018. There was an increase in the correlation between the two values up to 30°–40° for sites 3037 and 3084 as well. When the ALS points within different zenith angles were used to estimate canopy closure for site 3018, their correlations with EIV_{light} increased with increasing zenith angles, with the highest correlation when points from the whole hemisphere (angle of view 180°) were used.

6. Discussion

Estimation of understory light conditions using ALS data could supplement, or even replace, field-based methods. ALS-based canopy closure was shown to be a better predictor of understory light conditions than ALS-based canopy cover. However, as with field-based estimates of canopy closure using densiometer, hemispherical photographs or TLS, the estimates are scale-dependent. Zhao and Popescu (2009) noted that the estimation of LAI from ALS data, as in optical remote sensing, is also scale-dependent, even when not explicitly stated. The optimal resolution, in terms of angular intervals, for estimating canopy closure might be dependent on the point spacing of ALS data, as well as the characteristics of the site.

Generally, the correlations between the estimates of canopy cover and EIV_{light} increased with increasing variability in canopy cover within a site. The lower the variability, the more difficult it was to predict understory light conditions from the estimates of canopy cover. This is reflected in the higher correlations between canopy cover and EIV_{light} when adjacent open and forest sites were considered as single sites than when they were considered as individual sites (Table 2).

Canopy closure corresponds to a larger angle of view (180°) when compared to canopy cover and densiometer readings. When the angle of view, or the zenith angle, was progressively increased, canopy closure also increased, which supports the findings of Bunnell and Vales (1990) and Fiala et al. (2006), although these studies are more applicable to closed than open forests. The correlation with EIV_{light} also increased with increasing zenith angle. The estimates using ALS at an angle of view of 180° therefore provided a better estimate of canopy closure than densiometer readings.

The radial distance at which the canopy closure estimates reached a steady value was usually also the radius at which there was maximum correlation with EIV_{light}. Increasing plot radius beyond 50 m had little influence on canopy closure (Fig. 6A) or on the correlation with EIV_{light} (Table 3). This was probably because the addition of points beyond this distance would only increase the number of points in the zenith angle intervals closest to the ground (Fig. 2). This would have little influence on the estimated canopy closure since the occurrence, and not the number, of points in a particular angular interval is the deciding factor.

Canopy cover and canopy closure are not necessarily correlated. The heights of trees do not directly affect canopy cover since it is the vertical projection of the crown. Canopy cover from ALS could

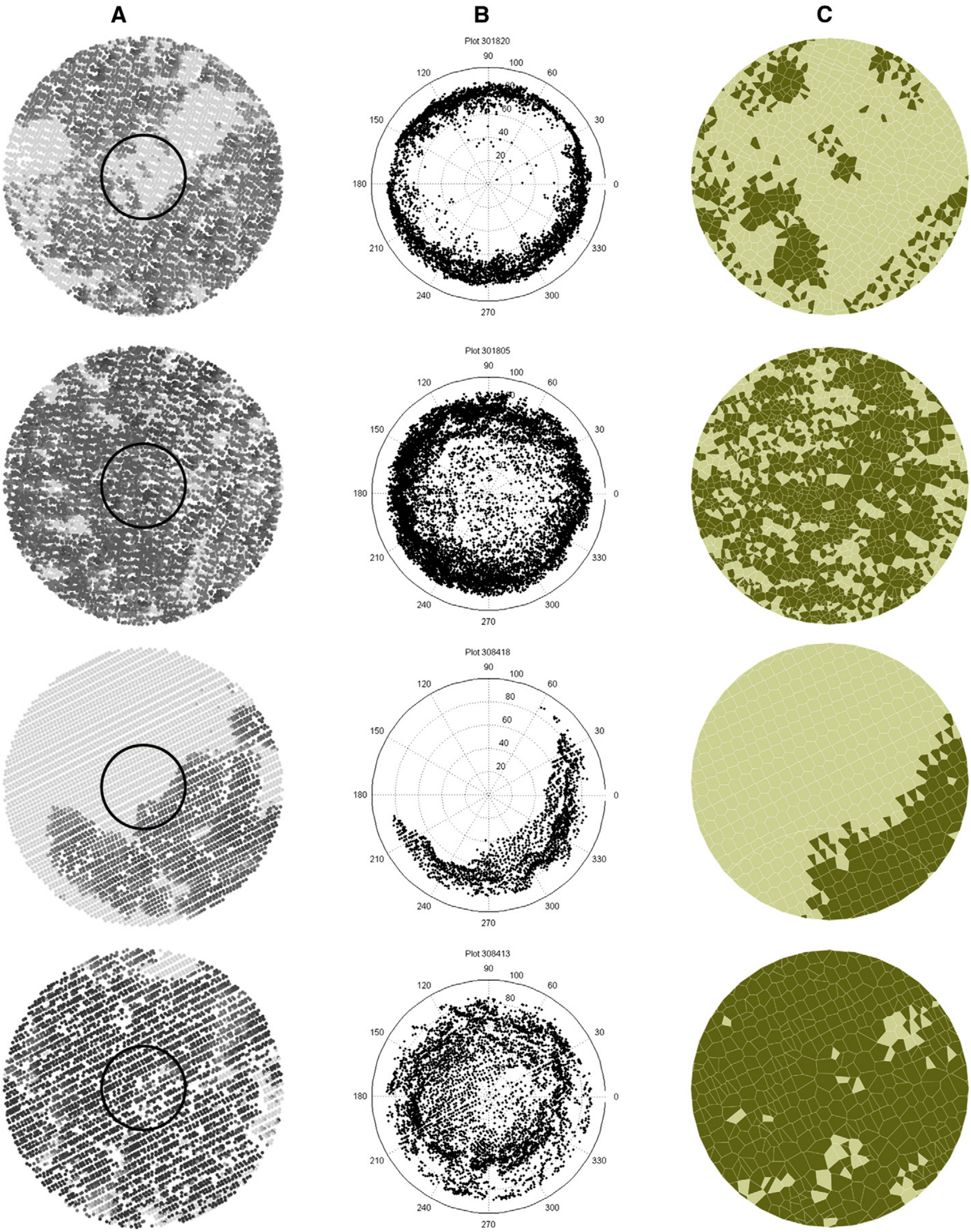

Fig. 5. (A) ALS points within 50 m from the plot centres of sample plots displayed by elevation. The 15-m radius circles are also shown. (B) ALS points at or above 1 m from the ground and within 50 m from the centres, plotted in the polar coordinate system, with the azimuth angle as the angular coordinate and the zenith angle as the radial coordinate. (C) Thiessen polygons generated from the ALS points within 15 m from the plot centres. The polygons in dark green are at or above 1 m from the ground.

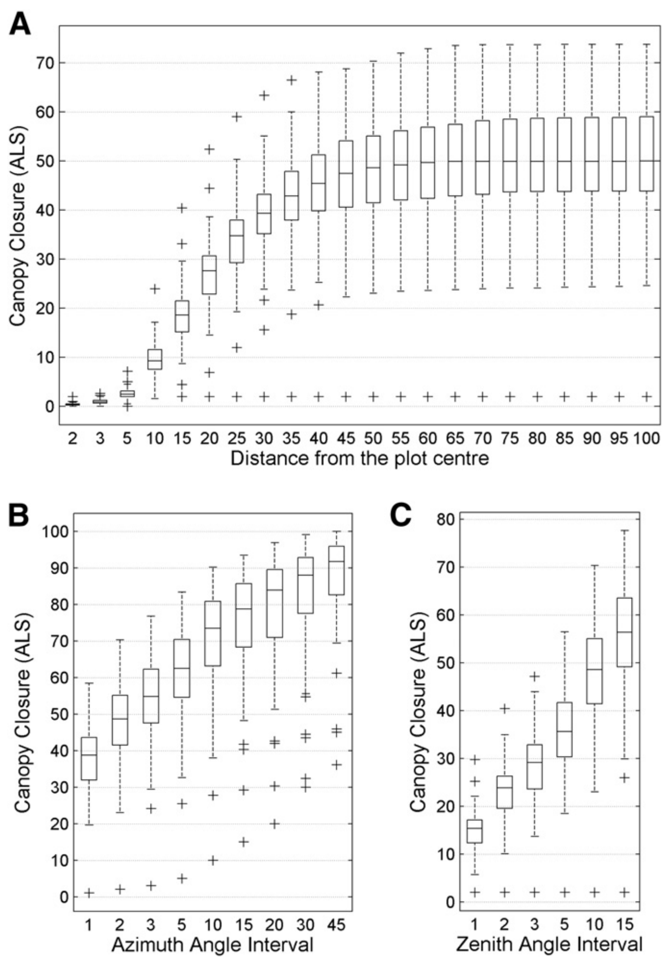

Fig. 6. (A) Estimated angular canopy closures for the 60 forest plots with different radii, with an azimuth angle interval of 45° and a zenith angle interval of 1°; (B) for a plot radius of 50 m and a zenith angle interval of 1°; (C) and for a plot radius of 50 m and an azimuth angle interval of 45°. When all the 60 plots were considered, plot radius of 50 m, azimuth angle interval of 45° and zenith angle interval of 1° provided the best correlation with Ellenberg indicator values for light for the 15-m plots.

have a correlation with the height of trees due to the increased presence of foliage in taller trees, assuming that they are detected by the sensor. However, canopy closure is expected to have a higher correlation with tree height, since a taller tree is more likely to appear to 'fall' towards the centre of the plot, or a lower zenith angle, and lead to an increased estimate of canopy closure. As tree height increases, more of the sky hemisphere is obscured with a resultant increase in canopy closure (Jennings et al., 1999). Conversely, in the case of a patch of trees, canopy cover could be almost 100%, with canopy closure much less if light reached the understory from a surrounding open area. Such effects could explain why closure was not highly correlated with canopy cover in this study (Fig. 7C).

The method based on Thiessen polygons provided an estimate of canopy cover based on area rather than the number of points. However, there are a few potential drawbacks. If an oblique pulse hits the ground under the crown, a ground polygon is generated inside the otherwise continuous crown, leading to underestimation of canopy cover. If there are shadows behind dense crowns, there could be errors in the estimations.

The correlation between the estimates of canopy closures from ALS data and using densiometer for site 3018 was the highest when ALS points within 40° from the zenith, providing an angle of view of 80°, were used for the estimation. The field-based canopy closure was the mean of four readings taken 2 m away from the centre of the plot in the four cardinal directions. The errors in our GPS locations in the forest plots could be up to 10 m and in the open areas, from 2 to 5 m, which also probably explains some of the outliers in the scatter plots. Nevertheless, this angle of view was similar to the findings in Minkova and Logan (2007), who used the method described in Englund et al. (2000), and found that the densiometer had an angle of view of 82.7°. Although densiometers can be used to quickly estimate canopy cover/closure at a few locations, ALS-based proxies would provide a much faster estimate of canopy closure across landscapes. These proxies are also more objective, and are less influenced by weather conditions.

Hemispherical photography provides good estimates of canopy closure and light penetration. However, in addition to being expensive and time consuming, illumination conditions and subjective thresholding of grey values, needed for classifying pixels as sky or canopy, cause errors in the estimation (Hanssen & Solberg, 2007). Densiometers are therefore considered cheaper and more efficient alternatives to hemispherical photographs, although they have a smaller angle of view (Fiala et al., 2006). They may be adequate for a rough estimate of canopy cover/closure; however it should be noted that they over-estimate canopy cover, and under-estimate the true (180°) canopy closure. The measurement using a densiometer is also prone to errors since the field technician has to simultaneously hold the instrument steady and calculate the number of squares covered by vegetation.

TLS and ALS have the advantage over hemispherical photographs that they are not affected by light conditions. However, there are differences between the parts of the canopy captured by the two laser scanners, with ALS being biased towards the tree crown, and TLS towards the base (Chasmer et al., 2006). Although the field-based techniques provide accurate estimates for a limited number of locations, ALS is better suited for canopy cover estimates at the landscape level. If ALS with a higher point density than the one used in this study could be used, it would perhaps improve the accuracy of the estimated canopy closure, with less influence from the tree trunks and branches than TLS and hemispherical photographs.

Use of waveform ALS should improve ALS-based canopy structure estimates by capturing more points from within the canopy. While discrete-return ALS often detects two or more echoes within the footprint of a laser beam, full-waveform ALS captures the entire return waveform within the footprint, and has been shown to be better for vegetation studies (Lindberg et al., 2012). The minimum distance between two objects in the path of the laser pulse required to distinguish them depends on the laser pulse duration; for example, for a pulse duration of 4 ns, the second object can be detected if its distance from the first is more than 60 cm, and it is not in the shadow of the first. Full-waveform ALS data are therefore able to capture many more points within the canopy than discrete-return ALS (Persson et al., 2005).

Discrete-return ALS is better suited for estimating vertical canopy cover than angular canopy closure, as they often fail to detect small within-crown gaps (Korhonen et al., 2011). Nevertheless, ALS-based canopy closure had a better correlation with light conditions, as represented by EIV_{light}, than canopy cover in this study. The intensity of a laser echo is related to the peak power of the laser pulse divided by the footprint area, known as the 'peak pulse power concentration'. The lower the peak pulse power concentration, the larger the foliage area required to raise the backscatter energy above the threshold for pulse detection (Hopkinson, 2007; Solberg et al., 2009). In this study, the footprint diameter of the laser beam was 50 cm, with a point density of 1.5 points m^{-2}. With a higher point density and a smaller footprint for discrete-return ALS, or with the use of full-waveform ALS, the accuracy of the estimates of canopy closure could be improved.

7. Conclusion

ALS-derived canopy variables has the big advantage that they can be rapidly estimated for extensive areas, and hence ALS may be better suited for large-area mapping of canopy variables than more accurate,

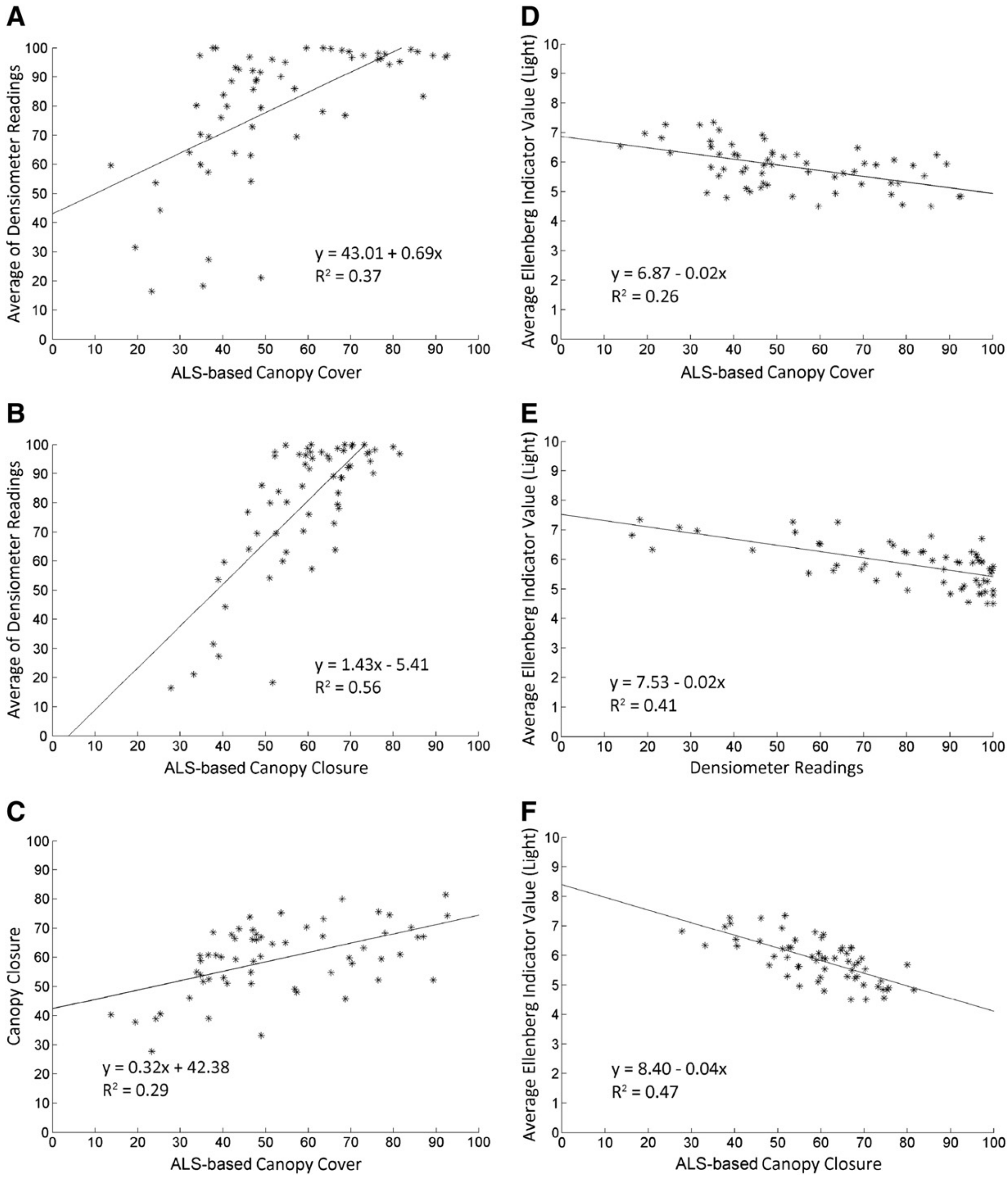

Fig. 7. Correlations between the ALS-based estimates of (A) canopy cover and (B) canopy closure with the average readings from densiometer; (C) between canopy cover and canopy closure, and (D) between canopy cover, (E) densiometer readings and (F) canopy closure with the average Ellenberg indicator value for light.

Table 3
Coefficients for Pearson correlations between ALS-based canopy cover, canopy closure and densiometer readings, and the average Ellenberg indicator values for light ($\mathrm{EIV}_{\mathrm{light}}$) for plant species within the 15-m radius plots in the forest sites (Cover15 — ALS-based canopy cover; Closure — ALS-based canopy closure; $\mathrm{EIV}_{\mathrm{light}}$5 — Average Ellenberg indicator value for 5-m radius plots; $\mathrm{EIV}_{\mathrm{light}}$15 — Average Ellenberg indicator value for 15-m radius plots). For the correlations between canopy closure and $\mathrm{EIV}_{\mathrm{light}}$, the values when the azimuth and zenith angle intervals were optimised for each site are shown in brackets.

	3018	3037	3084	All
Cover15 — Densiometer	0.62	0.47	0.81	0.61
Closure — Densiometer	0.71	0.47	0.56	0.58
Cover15 — Closure	0.84	0.74	0.69	0.40
Cover15 — $\mathrm{EIV}_{\mathrm{light}}$5	−0.65	−0.56	−0.60	−0.48
Closure — $\mathrm{EIV}_{\mathrm{light1}}$5	−0.79 (−0.84)	−0.61 (−0.74)	−0.72 (−0.86)	−0.70
Cover15 — $\mathrm{EIV}_{\mathrm{light1}}$15	−0.63	−0.58	−0.62	−0.52
Densiometer — $\mathrm{EIV}_{\mathrm{light1}}$15	−0.77	−0.66	−0.62	−0.64
Closure — $\mathrm{EIV}_{\mathrm{light1}}$15	−0.76 (−0.81)	−0.60 (−0.74)	−0.75 (−0.86)	−0.69

but also more laborious, time-consuming and, sometimes, subjective field-based methods. Angular canopy closure estimates from ALS have been compared with estimates from hemispherical photographs (Korhonen et al., 2011). All the previous studies compared fractional cover, or laser penetration rate, within a cylindrical space with the field-based estimates of canopy closure, showing these measures to be strongly correlated with LAI (Riaño et al., 2004). In this study, the hemispherical space around a point was used to develop an estimate of canopy closure more related to both the direct and indirect light experienced by a plant or an animal. The estimated angular canopy closure was an even better predictor of the ecologically relevant light regime below canopies, represented in this study by the average EIV_{light} for the species present in our test plots, than ALS-based estimates of cover or field-based estimates using a densiometer. The increasing availability of full-waveform ALS data is likely to make such ALS-based estimates of canopy cover and canopy closure even more representative of forest understory light conditions in the future.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: http://dx.doi.org/10.1016/j.rse.2013.02.028. These data include Google maps of the most important areas described in this article.

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