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Agricultural and Forest Meteorology xxx (2004) xxx–xxx

AGRICULTURAL AND FOREST METEOROLOGY

www.elsevier.com/locate/agrformet

Short communication

Estimation of leaf area index and covered ground from airborne laser scanner (Lidar) in two contrasting forests

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Received 7 July 2003; received in revised form 16 December 2003; accepted 15 February 2004

Abstract

Two canopy properties, leaf area index (LAI) and covered ground (CoverGnd), were estimated using hemispherical photography of three oak (*Quercus pyrenaica*) and eight pine (*Pinus sylvestris*) forest plots in Sierra de Guadarrama (central Spain). Pulses from airborne laser scanner (Lidar) that hit the surface on the exact location (within centimeter resolution) of the photographs were analyzed and separated by different radius size (from 0.5 to 20 m). The correlation between Lidar and hemispherical photography estimates of canopy properties was highly significant, but was affected by the type of forest and the radius size. CoverGnd was better estimated using a small radius size (2.5 m, equivalent to one fourth of canopy height), while LAI was better estimated using a larger radius size (7.5–12.5 m, equivalent to the entire canopy height). In general, the smaller the tree, the shorter the radius was that must be used to select Lidar data, and the best Lidar estimator of canopy properties was the percentage of canopy hits. Overall oak canopies showed better results than pine forest. The poorer estimation in pine forest plots was probably due to the larger foliage and branch clumping of pine versus oak canopies. Lidar data could be used to produce high-resolution regional maps of the canopy properties studied.

Keywords: Leaf area index; Covered ground; Hemispherical photography; Lidar

1. Introduction

Leaf area index (LAI) is a critical variable in ecosystem modeling due to its influence on bio-geochemical cycles (Gower et al., 1999). Direct LAI determinations are time consuming and frequently destructive, so they cannot be collected in practice within an appropriate spatio-temporal scale. The only possible method to obtain LAI values at a high sampling rate or for a larger spatial scale is by analyzing the gap fraction (van Gardingen et al., 1999), using either hemispherical photography or other indirect techniques (e.g. LAI-2000 LiCor). These indirect techniques cannot be applied, however, at the landscape

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doi:10.1016/j.agrformet.2004.02.005

or regional levels. Passive optical remote sensing can indirectly estimate LAI at these larger scales. The problem encountered with these sensors is the saturation at high levels of LAI (Chen and Cihlar, 1996). Another limitation is that the presence of understory vegetation affects the reflectance values and introduces significant noise to the estimation of LAI (Chen and Cihlar, 1996). Thus, passive optical remote sensors are valuable to cover regional and global scales, but are not accurate enough to cover local scale. As shown in recent reviews, airborne laser scanner (Lidar) can cover this gap in the scaling-up process, since it does not saturate for high LAI values (Lefsky et al., 2002) and can better separate the understory. Covered ground (CoverGnd) can be estimated from passive optical remote sensing (Larsson, 1993). However, its accuracy depends on the size of the vegetation patches in relation to the pixel size. If the pixel size is too large compared to the vegetation patch, each pixel is not identified individually as vegetation or ground. In those cases, the estimation relies on this mixed spectral response of canopy and surface, which is often a non-linear mix. On the other hand, Lidar is a direct estimator with a 1:1 relationship between percentage of Lidar canopy hits and CoverGnd (Ritchie et al., 1992).

The main purpose of this study was to assess the capacity of Lidar to estimate LAI and CoverGnd of two contrasting and common types of forests (oak versus pine forests), addressing three specific goals: (i) to determine the best transformations of the laser pulse measurements to mach the indirect, ground-based estimates of LAI and CoverGnd, (ii) to select the Lidar radius size that provides the best agreement with the indirect ground-based estimates, and (iii) to explore the relationships between Lidar data and the indirect ground-based estimates for each forest type. Most studies attribute the error in the estimation of LAI and CoverGnd to a poor georeferencing between ground-based measurements and acquired remotely sensed data. These validations were performed for average plot measurements. This paper explores the relationship between the information extracted from Lidar data and LAI and CoverGnd estimated from each hemispherical photograph, georeferenced within centimeters, significantly enhancing the power for validating remotely sensed estimations of canopy properties.

2. Materials and methods

2.1. Study site

The study site was located in the vicinities of Canencia, in the Sierra de Guadarrama, about 50 km north of the city of Madrid, Spain (longitude, 3.74–3.77°W; latitude, 40.87–40.90°N). Oak forest (*Quercus pyrenaica* Willd.) dominate the study area in the northwest. The natural and planted Scots pine forests (*Pinus sylvestris* L.) were in the southeast. Oak trees (mean height = 8 m, S.D. = 2 m) were generally shorter than the pines (mean height = 13 m, S.D. = 3 m). The oak forest plots were located at a lower altitude and on more gentle slopes than the pine forest ones.

2.2. Field measurements

Two GPS units (double differences integer solution) provided accurate positions at the border of the forest. Field topography was used in locating the center of the field plots in the forest. Three plots were located in oak forest and eight were located in pine forest. A 30 m measuring tape was placed on the ground within each plot in the N–S direction using a KB-14/360R Suunto compass (Suunto, Finland). A hemispherical photograph was taken every meter, making a total of 31 photographs for each plot, except for two oak forest plots, where 13 photographs were taken, one every 5 m, in two perpendicular transects in the N–S and E–W direction. These two plots were measured before we changed the sampling strategy to single transects to collect more measurements. All plots were measured on 8 September 2002, close to the date of the Lidar flight, except for two oak forest plots, which were measured on 23 June 2002.

2.3. Lidar data acquisition and processing

The test area of 2 km × 2 km was overflown in 16 August 2002 with Toposys II system (http://www.toposys.com), recording high-density first and last Lidar returns with small footprints. The diameter of the laser footprint was about 0.45 m and the total average first and last laser pulse density for our study plots was 9.3 points/m^2. The pattern was different in the across and along track direction, with about one first and last pulse every 1.73 and 0.11 m, respectively.

We generated vegetation height above the ground for each laser pulse using interpolated values extracted from a digital terrain model (DTM). The data provider produced the DTM based on the bisection principle (von Hansen and Vögtle, 1999). We applied spline function interpolation in Matlab 6.0 (The MathWorks Inc., http://www.mathworks.com, USA) in order to obtain the height above the ground.

2.4. Hemispherical photography

LAI and CoverGnd were quantified by hemispherical photography. Photographs were taken at 1 m above ground level using a horizontally-leveled digital camera (CoolPix 995, Nikon, Tokio, Japan) with a fish-eye lens (FCE8, Nikon). All photographs were taken under overcast conditions to ensure a homogeneous illumination of the overstory canopy and a correct contrast between the canopy and the sky. The resulting images were analyzed for canopy openness using Hemiview canopy analysis software version 2.1 (1999, Delta-T Devices Ltd., UK). LAI was estimated with Hemiview as half of the total leaf area per unit ground surface area, based on the ellipsoidal leaf angle distribution. Calculation of LAI by Hemiview involves use of Beer's Law, which can be expressed as follows:

$$G(\theta) = \exp(-K(\theta) \times \mathrm{LAI}) \quad (1)$$

where G is gap fraction, and $K(\theta)$ is the extinction coefficient at zenith angle θ (±4.5°). LAI calculated is termed effective LAI, since it does not account for non-random distribution of foliage and includes the sky obstruction by branches and stems. GndCover was defined as the vertically projected canopy area per unit ground area. It gives the proportion of ground covered by canopy elements as seen from a great height, and is calculated assuming the canopy has an ellipsoidal distribution:

$$\mathrm{GndCover} = 1 - \exp(-K(x, 0) \times \mathrm{LAI}) \quad (2)$$

where $K(x, 0)$ is the extinction coefficient for a zenith angle of zero, x is the ellipsoidal leaf angle distribution.

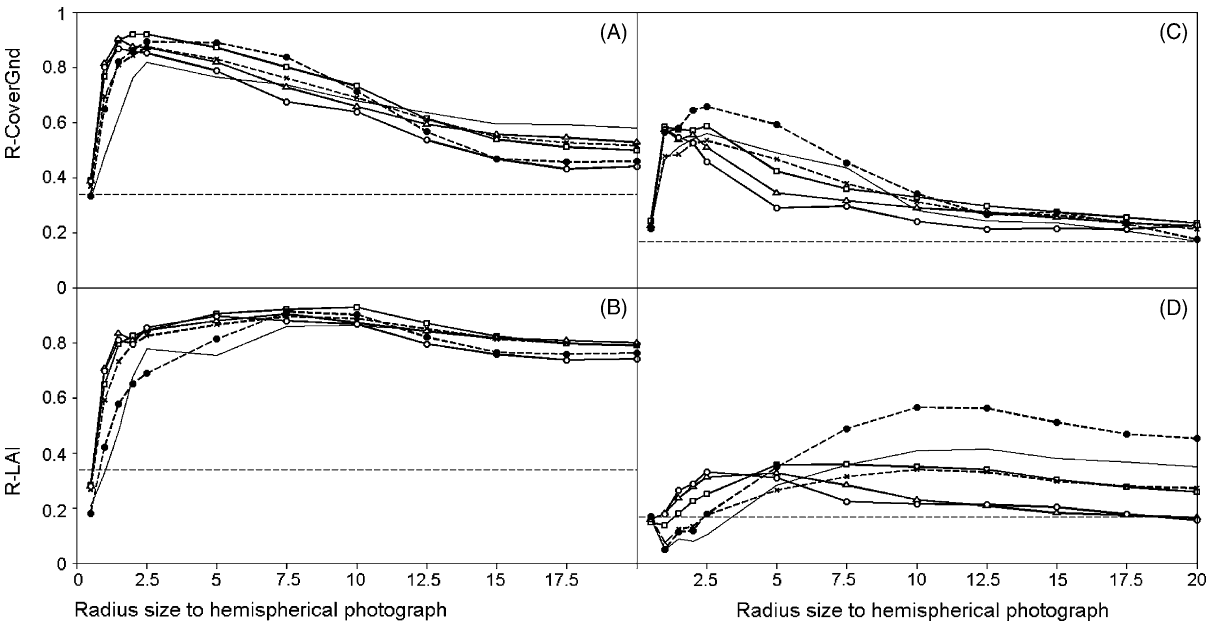

Fig. 1. Correlation coefficients (R-Pearson) between Lidar measurements and CoverGnd and LAI for oak forest (A and B, $n = 57$ hemispherical photographs) and for pine forest (C and D, $n = 239$ hemispherical photographs) at different radii. Solid line (—), is the 50 percentile; line with open squares (–□–), 75 percentile; line with open triangles (–△–), 95 percentile; dashed line with crosses (- -×- -), mean; line with open circles (–○–), maximum; dashed line with close circles (- -●- -), % of canopy hits; dashed line (- - -) indicates minimum significant value for R-Pearson ($P = 0.01$).

2.5. Relationship between Lidar and LAI or CoverGnd

LAI and CoverGnd are dependent on forest structure up to a certain radius size. The purpose of this paper is to assess the capacity of Lidar to estimate these parameters and the most appropriate spatial scale where Lidar data (i.e. pulse information) must be pooled for each parameter in each of the two forest types. We processed the Lidar information for different radius, from 0.5 to 2.5 m (every 0.5 m) and from 2.5 to 20 m, at radius intervals of 2.5 m. We calculated for each specific radius different Lidar variables to check for the best estimator. The predictive variables were: 50, 75, and 95 percentile of heights; average height, maximum height and percentage of canopy hits. The percentage of canopy hits was calculated assuming that all laser pulses within a height <3 m were understory and ground hits. Note that the hemispherical photograph was always taken above the understory vegetation, although in most cases, no understory vegetation was present.

3. Results

The estimations of LAI and CoverGnd from hemispherical photography and from different variables obtained from the Lidar data were significantly correlated and the correlation varied for different radii (Fig. 1). There was an optimum radius at which the coefficient of correlation was maximized, an inflexion point, and

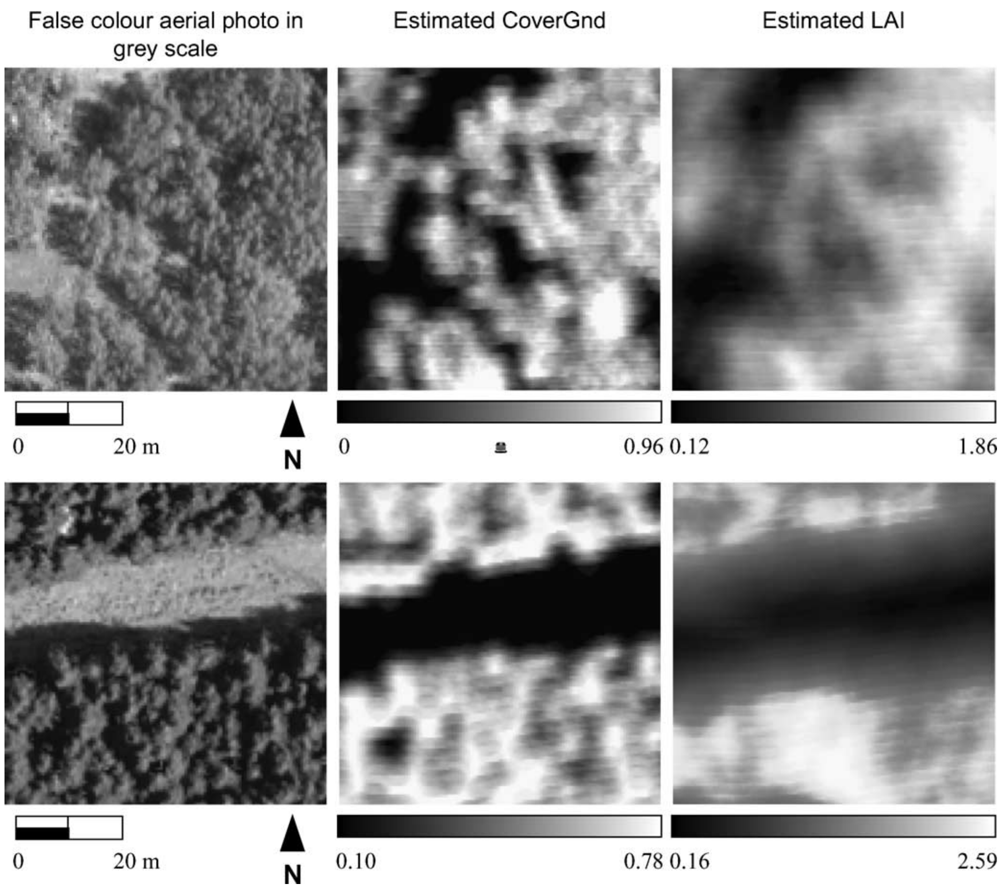

Fig. 2. Maps of estimated covered ground (CoverGnd) and leaf area index (LAI) for an oak forest plot (upper series) and a pine forest plot (lower series).

the relationship lost strength in both directions. There was also a dramatic decrease in the correlations for radii less than 2.5 m. Lidar data taken at relatively short radii (<2.5 m) always estimated CoverGnd better, while LAI was estimated better by longer radii (7.5–12.5 m). LAI was better predicted with Lidar data for radius of 7.5–10 m for oak forest whereas the best range for pine forest was 10–12.5 m. Estimations were better for oak forest plots than for pine forest plots. All variables calculated from Lidar data correlated well with hemispherical photography variables for the oak forest plots, but only percentage of canopy hits correlated well in the case of the pine forest plots. This estimator was also the most sensitive to the radius size used to select Lidar data.

Values from regressions were used to produce high-resolution maps of CoverGnd and LAI and for oak and pine forest plots from Lidar data (Fig. 2). In agreement with the conclusions from Fig. 1, CoverGnd rendered a relatively fine-grained map, while LAI rendered a relatively coarse-grained map.

4. Discussion

4.1. Lidar versus ground-based estimation of canopy properties

Estimation of forest stand structure attributes is among the areas of application of Lidar remote sensing that has been more rigorously evaluated (Lefsky et al., 2002). However, we have found an important influence of the protocols (e.g. radius size used to select Lidar data, way of transforming Lidar data) on the accuracy of the estimations obtained with Lidar, pointing to the need of thorough revisions and specific calibrations for each study case.

CoverGnd was measured considering the zenith angle (±4.5°) of the hemispherical photograph. The radius covered by the photograph at a height was tan(4.5°) × height, which gives a radius of influence between 0.6 and 1.0 m for vegetation heights in between 8 and 13 m. Thus, CoverGnd best fit with Lidar data should have been at 0.6–1.0 m in our study case, but it was 2.50 m (Fig. 1). This was related to the laser pulse density, since only one first and last pulse every 1.73 m in the across track flying directions were recorded. Considering shorter radii than 2.5 m would have implied more chances of not finding any Lidar data to relate to the ground-base data. Therefore, CoverGnd could be better related to radii shorter than 2.5 m, but only if higher laser point density is available. LAI was better estimated at longer radii than CoverGnd (Fig. 1). This was explained by the fact that CoverGnd was calculated from the hemispherical photography at zenith angle whereas LAI was based on the overall information of the semi sphere. The existence of an inflexion point in the relationship between Lidar and ground-based estimated LAI, with decreases in the correlation on both sides of this point indicates that we have explored the proper range of distances. Among the different transformations of Lidar data, percentage of canopy hits was the best estimator. Magnussen and Boudewyn (1998) found this variable to be related to true LAI, working at plot level with average LAI values, and Ritchie et al. (1992) selected this variable to predict CoverGnd. We found out that this estimator was more sensitive to the radius size used to select Lidar data than the others. For example, oak forest CoverGnd was best predicted by percentage of canopy hits at 2.5 m, but this variable rendered poorer results than the other ones for longer radii.

The noise in the relationship between ground-based estimations of canopy properties and Lidar estimations could be attributed, at least in part, to the different point and angle of view of the hemispherical photography versus Lidar. Hemispherical photography registers the canopy punctually from the ground looking up, whereas Lidar scans the canopy from above. Therefore, there were areas seen in the hemispherical photographs, but obscured in the Lidar data, and vice versa. In addition, Lidar measurements undersampled the study area in the across track direction, with one laser pulse every 1.73 m. Lidar did not cover a distance of about 1.28 m between footprints in this direction, because footprint size was only 0.45 m. Both discrepancies can be expected to be particularly critical, if the foliage units of the study canopy depart significantly from a random spatial distribution. Chen and Cihlar (1996) found out that effective LAI, although less addressed by remote sensing studies than true LAI, is better related to reflectance because the sensor actually measures the energy reflected by the surface. This can be the case also for Lidar, since it measures the light (laser pulses) reflected by the surface. It is noteworthy that any correction to account for the clumping effect could also be applied a posteriori to convert Lidar estimates of effective LAI into estimates of true LAI.

Canopy height determined the radius size to be considered from each particular sampling point when selecting the Lidar data, and this was different for the different variables. Estimation of LAI from Lidar data was best when data were selected using a radius similar to the height of the canopy (8 m for the oak and 13 m for pine forest plots) and estimations of CoverGnd were best using radii of around one fourth of the canopy height.

4.2. Differences among the two types of forest

The significant differences in stand and canopy structure between the two types of forest studied translated into differences in the agreement between hemispherical photography and Lidar variables for each forest. Correlation between variables obtained from hemispherical photography and from Lidar data was noisier in the pine than in the oak forest plots, suggesting that regression parameters and accuracies are forest specific and, thus, caution is needed when using results obtained with one type of forest to estimate canopy properties from Lidar data with a different one. Canopy height and leaf type (needles versus broad leaves) seem to be two features particularly important in this respect.

Agreement between Lidar and ground-based data was significantly better for the oak forest than for the pine forest. Pine needles, as compared to broad, flat leaves such as those of oaks, pose two main challenges for the estimation of canopy properties from hemispherical photography: (i) the optical and digital resolution needed to capture such small foliage units, (ii) the tendency of needles to be strongly clumped, which is against the basic assumption of any indirect estimation of LAI. In practice, effective LAI and true LAI are nearly identical in broadleaf canopies. However, in conifer canopies, where there is strong clumping, it becomes necessary to estimate the clumping factor by either direct of indirect means to obtain a more realistic LAI value (Chen and Cihlar, 1996). Lidar intensity values could help to perform this correction, but intensity is related to the reflectance and size of the intercepted surface, two factors difficult to separate.

4.3. Conclusions

Lidar data could be used to produce high-resolution maps of CoverGnd and LAI since a good correlation was found with hemispherical photography. These maps could be used as an intermediate step in the process of scaling up these variables from the punctual or local value to the regional and global scale. The radius size used to select Lidar data, which depends on both the type of forest and the type of variable to be estimated, must be taken into consideration. CoverGnd was better estimated at a small radius while estimation of LAI required larger radii. This finding will determine the proper spatial sampling of the Lidar data needed with small footprint and also the appropriate size of full-digitized large footprint data. The best predictor was the percentage of canopy hits. According to this study the smaller the trees the shorter the radius to be considered for estimations of LAI. Further research should be carried out to analyze the influence of foliage clumping in the hemispherical photography versus Lidar estimations of canopy properties, providing a more holistic model that could also account for the difference in viewing geometry of each sensor. The relationships found here, which allow for a more precise usage of Lidar data to estimate canopy properties, lay the groundwork for future studies that use these relationships to map biophysical variables and shows the potential for a new class of large-scale ecological research.

Acknowledgements

We wish to acknowledge the Comunidad Autónoma de Madrid (Spain) (project 07M/0067/2001) and European Spread project (EVG1-CT-2001-00043). A Fulbright Grant and the financial sponsorship of the Spanish Ministry of Education supported David Riaño. We also thank the Department of Geography of Alcalá, Javier González and the Division of Forest Fires of the Autonomous Region of Madrid (especially Álvaro Sánchez), for helping with the fieldwork.

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