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Mapping plant area index of tropical evergreen forest by airborne laser scanning. A cross-validation study using LAI2200 optical sensor

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ABSTRACT

Leaf area index estimates in dense evergreen tropical moist forest almost exclusively rest on indirect methods most of which being of limited accuracy or spatial resolution. In this study we examine the potential of full waveform Aerial Laser Scanning (ALS) to derive accurate spatially explicit estimates of Plant Area Index (PAI).

A discrete representation of the forest canopy is introduced in the form of a 3D voxelized space. For each voxel (elementary volume, typically one cubic m) a first estimate of local transmittance of vegetation is computed as the ratio of the sum of energy exiting a voxel to the sum of energy entering the same voxel. A spatially hierarchical model is subsequently applied to refine estimates of individual voxel transmittance. Plant area density (PAD) profiles are then computed from the local transmittance values by applying Beer Lambert's turbid medium approximation. PAI values are obtained from vertical integration of PAD profiles. The model is shown to be robust to low sampling intensity and high occlusion rates.

We further compared simulated values of gap fraction obtained by ray tracing for 5 angular sectors with in situ LAI2200 measurements taken at 135 positions in a 0.5 ha forest plot located in the center of the scene. The overall patterns of simulated and measured values (average value per inclination and pattern of variation along a 70 m transect line) were highly consistent. A slight but systematic discrepancy was observed along the inclination gradient, gap fractions derived from ray tracing in the voxelized scene being slightly lower than the measured values. This difference might be the consequence of multiple reflections which have been found to bias gap fractions estimates produced by LAI2200.

PAI estimates derived from LAI2200 measurements (either simulated 6.8 or observed 5.9) are much lower than the PAI derived from vertical integration of local PAD (13.6). This large difference reflects the fact that distribution of foliage is strongly spatially structured and that this structural information is not properly accounted for in PAI estimates derived from mean gap fraction per elevation angle. After adjusting local transmittance to match mean LAI 2200 profiles the PAI at plot level was found to be 13.2 $m^2 \cdot m^{-2}$.

We conclude that Aerial Laser Scanning can produce accurate maps of Plant Area Index over large areas with unmatched efficacy, accuracy and ease. This should be of major relevance for many forest ecological studies.

1. Introduction

Leaf area index (LAI) defined as one-sided green leaf area (m^2) per unit horizontal ground surface area (m^2) is a key vegetation characteristic as foliage surface mediates the interaction between vegetation and the atmosphere (radiation uptake, precipitation interception, energy conversion and gas exchange) (Monteith and Unsworth, 1990). For instance LAI is required for upscaling gas exchange measurements from leaf to canopy. The ability to accurately describe the change of leaf area index over space and time in tropical evergreen forests is regarded as an important step toward improvement of current global dynamic vegetation models (Wu et al., 2016).

However LAI has proven difficult to estimate in tall dense evergreen tropical forests. To date direct destructive measurements of leaf area in tropical moist forest at the landscape scale have been conducted only once to our knowledge (Olivas et al., 2013). Most measurements are indirect and fairly crude. Litter fall collection which may be considered a benchmark method in temperate forest (Bréda, 2003) cannot yield accurate estimates due to the unknown and highly variable leaf turnover rates in extremely diverse tropical forests (Laurans et al., 2012). Ground based passive optical methods such as hemispherical photography or

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large view angle optical sensor such as LAI2200 also suffer from a series of well-known limitations (Bréda, 2003). One significant shortcoming of such methods is the underlying assumption that the canopy is spatially homogeneous around sampled positions. When the actual canopy leaf distribution deviates from a random distribution, LAI is underestimated (Mussche et al., 2001) unless a proper clumping factor is previously calibrated. Another significant shortcoming is that the actual forest volume sampled at any location where measures are acquired with such optical sensors is ill-defined (the forest volume sampled is different in the different directions) and spatial heterogeneity is difficult to accommodate. Airborne or spaceborne passive remote sensors have also been used to estimate LAI but often suffer from signal saturation in areas of dense vegetation and high biomass and are therefore inadequate for use in tall dense forest (Zheng and Moskal, 2009).

Lidar is an active remote sensing technology that measures distance by measuring the round-trip time for a laser pulse to travel between the sensor and a target. In airborne laser scanning (ALS), the downward high-frequency emission of low-divergence laser beams from an airborne platform provides measurements over small footprint areas at ground level — typically with sub meter diameter — and accurate data on the position of targets below. A dense pattern of signal returns is obtained thanks to the instrument scanning system. ALS systems have the unique advantage over passive optical sensors of penetrating the vegetation and have early on been identified as a potential source for mapping LAI in forested landscapes (see references below).

Many studies use the term LAI but actually refer to Plant Area Index (PAI) as in most cases no separate estimates of the contribution to canopy of photosynthetically active versus non photosynthetically active structures are available. In a forest context, non-photosynthetically active supporting structures that interact with light may contribute significantly to light interception (Woodgate et al., 2016).

Most efforts in the last decade to use ALS for estimating PAI in forests have concentrated on retrieving “Effective PAI” (i.e. neglecting clumping and not distinguishing woody material from leaves) typically by means of correlative approaches. Morsdorf et al. (2006) working in pine forest correlated PAI estimates derived from hemispherical photographs and a laser penetration index. Jensen et al. (2008) also used a correlative approach between effective PAI (estimated using a hemispherical optical sensor) and a set of lidar metrics in a boreal forest. A similar approach has also been successfully developed by others in boreal forest (Korhonen et al., 2011; Solberg et al., 2009) and recently in tropical forest (Tseng et al., 2016).

Schneider et al. (2014) reconstructed from full waveform aerial lidar data a forest scene in the form of a $2 \times 2 \times 2$ m^3 voxel grid with vegetation represented as a turbid medium. To do so they first calibrated an empirical relation between field measured PAI and an algebraic expression of the total number of echoes and the number of ground echoes. In a second step the estimated PAI was vertically distributed per $2 \times 2 \times 2$ m voxel based on vertical point cloud density. Even if both leaf-on and leaf-off acquisitions were available, the proposed method might not properly reproduce the vertical distribution of foliage since the occlusion responsible for unbalanced sampling of the different canopy strata is not considered.

Strong limitations to the empirical approaches are the need for calibration data, locally or at least per forest type, and the difficulty to predict the way acquisition parameters (flight height and scanning angle) will affect PAI estimates when those are modified from one campaign to another (Korhonen et al., 2011).

Recent efforts to develop more mechanistic models to retrieve PAI from Aerial Laser Scanning include the work by Song et al. (2011), Ma et al. (2015) and by Detto et al. (2015). The latter introduces a stochastic radiative transfer modelling framework to process multiple return ALS data based on the earlier work of Shabanov et al. (2000) and Titov (1989). The model provides two “penetration functions”: the probability for a beam with angle s to intercept fewer than k leaves up to depth z, and the probability for a “leaf” at depth z to be the kth contact along the beam path. While the model introduces a maximum return number to account for laser beam extinction, it does not take into account that a given return can embed more or less energy depending on the return number and rank. For instance, a single return is treated in the same way as a first return among multiple returns. When applied to real data sets the authors noted that including third or higher rank of return led to a reduction of PAI estimate. They suggested that this might be due to those returns having a low signal to noise ratio. They finally recommended “using only the first and second returns and applying a 10–15% correction for the bias observed in simulations (inhomogeneous simulation results for estimates based on two returns)”. No validation data of independent PAI measurement for the same area and same site were provided in their study.

Ma et al. (2015) adapted a modelling framework previously developed for large footprint lidar (Ni-Meister et al., 2001). To cope with missing data (incomplete spatial coverage) of small footprint lidar they mixed leaf area estimates from small foot-print full waveform analysis and PAI estimates derived from 0.5-m resolution Canopy Height Model (CHM). PAI estimates were derived from CHM by taking the fraction of CHM pixels of zero elevation in a 10×10 m area as a surrogate for transmittance and then applying Beer-Lambert's law. Unfortunately, the two PAI estimates showed little consistency where both were available. In that study validation data were also limited. The approach developed by Song et al. (2011) is based on the beam-contact frequency in each layer using a point-quadrat method initially applied to Terrestrial Laser Scanning data (Hosoi and Omasa, 2006). In their voxel-based approach only first returns are considered, thereby not making full use of the detection capability of modern full waveform lidar systems.

Previously Armston et al. (2013) and Chen et al. (2014) proposed a physically based method to retrieve Pgap (gap probability) from full waveform ALS. However, they did not propose a method for converting this transmittance estimate into PAI.

The main objective of this study was therefore to examine the potential of ALS to map PAI in dense evergreen forest. Contrary to most previous studies cited above (but not all, see Song et al., 2011 for instance) we do not restrict ourselves to mapping *effective* PAI but rather try to capture *true* PAI which is a more meaningful feature from an ecological point of view (more tightly related to true LAI). Indeed, one of the main advantages of lidar over in situ optical methods is that it may yield estimates of transmittance which are explicit in 3D, thereby providing a straightforward way of addressing vegetation clumping.

The manuscript is organized in the following way. In the Material and methods section, after a short presentation of ALS data and field data sets collected for the study, we introduce a physically based model of light interception by vegetation which benefits from well-established models of lidar wave form. We explain the statistical model which allows the estimation of PAI while taking full advantage of the 3D explicit information provided by lidar. In this section we also briefly describe the ray-tracing model used in the validation step to simulate LAI2200 sensor from a 3D distribution of PAD.

The Results section is divided into three subsections. Section one presents a sensitivity analysis of the predicted PAI and Plant Area Density profiles which PAI is derived from to three key parameters: the discretization step size (voxel size), the pulse density (number of pulses emitted per unit ground area) and the pulse energy fragmentation model.

In section two we compare actual LAI2200 directional transmittance measurements with simulated LAI2200 measurements obtained by ray tracing in the 3D voxel space assuming a spherical leaf distribution angle (and hence isotropic transmittance). We also explore the effect of a non-spherical function to describe the foliage inclination distribution function.

In section three we compare estimates of PAI derived from LAI2200 measurements (either actual or simulated by ray-tracing) with those obtained by vertical integration of elementary voxel Plant Area Density.