Estimation of Spatial Distribution of Leaf Area Density in Canopies from Terrestrial LiDAR Point Clouds

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1. Introduction

Leaf area is a key variable of forest ecosystems functioning, as it controls energy, water and carbon exchanges between canopy and atmosphere. Quantifying and understanding these fluxes require a fine scale 3D description of vegetation structure, including the spatial distribution of leaf area density.

Leaf Area Densities (LAD, m^2/m^3) are the one-sided areas of leaves per unit of volume. Their vertical integration provides leaf areas per unit of ground surface, i.e. the Leaf Area Index (LAI, m^2/m^2), which is key variable for parametrization of ecophysiological and 3D radiative transfer models in forests. Yet, measuring LAD manually is complex and time-consuming and hemispherical photos methods are limited by vegetation clumping and are not designed for 3D estimations.

LiDAR technology has the potential to capture at high-throughput the required level of details for 3D description of canopy structure. While space-based or aerial LiDAR cover large areas, the size of their footprints and occlusion of signal limit the fine quantification of 3D spatial distribution of canopy components, in particular in medium to low vegetation. Terrestrial LIDAR operates from the ground level and provides high-density point clouds. This sensor has been widely used to assess wood volumes in forest inventories, generally relying on a discrete reconstruction of trunks and large branches.

The use of terrestrial LiDAR to quantify leaf area is limited by significant bottlenecks. First, the appropriate choice of variables and statistics of interest for relating point cloud to LAD is still debated. Second, beam divergence affects the sampling of heterogeneous surfaces (Béland et al., 2011), while interactions between impulsions and canopy elements depend on laser characteristics and vegetation material properties, involving complex physical processes. Third, a low number of sampling beams can bias LAD estimators, and may even preclude providing estimations in some areas of the scene (Pimont et al., 2018). The present work aimed at disentangling these various sources of biases and errors, and proposed unbiased methods for LAD estimations in forest plots from terrestrial LiDAR point clouds.

2. Methods and data

We relied on a statistical approach relating metrics from TLS point-clouds and attenuation coefficient of vegetation within elementary volumes called ‘voxels’. Our work characterised and limited the sensitivity of this approach to statistical biases, vegetation structure and sensor properties.

2.1 Theoretical estimation of LAD

The first step focussed on the evaluation and correction of statistical biases inherent to the various inversion methods of transmittance described in the literature. We relied on a theoretical framework to control vegetation properties and sampling with numerical references for LAD (Pimont et al., 2019).

Such simulations allowed testing promising variables, and formalizing biases in order to rigorously develop and compare unbiased estimators. A specific effort was put in making use of all geometric information available from TLS data, i.e. free path explored by beams within voxels before interception.

A maximum likelihood for the coefficient of attenuation within a given voxel was rigorously retrieved and corrections for both low sampling configurations and size of leaf elements were implemented (Pimont et al., 2018). Confidence intervals associated with this unbiased estimator were also provided.

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2.2 Test of LAD estimators on actual tree branches

Theoretically unbiased estimators were tested at branch scale in laboratory conditions under various scanning conditions and compared with destructive references (Soma et al., 2018).

Three tree species of distinct leaf morphology were selected to evaluate the quality of LAD estimators in a range of structural diversity. Branches were scanned with two LiDAR instruments relying on two different technologies, namely phase-shift and time-of-flight instruments. Scans were performed from distances ranging from 2.5 m to 20 m. Series of scans were conducted on fully foliated branches, half-foliated and defoliated branches in order to extent the range of sampled LAD.

Leaves were manually harvested, weighted and 2D flat-scanned after each step to retrieve reference biomass and area of leaves for each branch. This step allowed testing robustness of LAD estimators regarding biases related with actual vegetation structure (clumping effect/voxel size, leaf size and morphology) and with instrument limitations (sampling variations, beam divergence and noise). An empirical correction factor H was estimated to account for these effects in the various tested configuration, resulting in the LAD estimate $\widetilde{LAD}$:

$$\widetilde{LAD} = \frac{H}{G}\tilde{\Lambda} = \frac{H}{G\sum z_e}\left(\mathrm{Ni} - \frac{\sum_{hits} z_e}{\sum z_e}\right) \qquad (1)$$

with z_e the effective free path of beams within a voxel, $\sum_{hits} z_e$ the sum of z_e for intercepted beams only, and G the effective area of interception of leaves, generally assumed to be equal to 0.5.

2.3 Field estimation of LAD at tree scale

The developed LAD estimators were applied to 15 isolated trees, scanned from 6 viewpoints.

We used LAD unbiased estimators and calibrations developed in previous steps to estimate total tree leaf areas and LAD profiles. Absolute references were obtained from manual harvest. This field campaign allowed evaluating our method, test the robustness of the approach and identify its limits.

2.4 Influence of sampling and estimations in occluded volumes with kriging

Further analyses were conducted with a virtual scene representative of a forest plot in which the reference 3D distribution of LAD is known -contrary to field experiments (Soma et al., 2021).

First, the aim of this numerical experiment was to evaluate the magnitude of biases and errors resulting from vegetation heterogeneity and sampling limitations at plot scale. Regarding references and confidence intervals, we disentangled the role of number of scans and voxel size on LAD estimations.

Second, we used this scene to develop a specific kriging method to provide an unbiased estimator for LAD estimation in poorly sampled and occluded areas (Soma et al., 2020).

3. Results and discussion

3.1 A theoretically unbiased LAD estimator

The numerical framework allowed the comparison of several LAD estimators regarding their potential biases and variances (Pimont et al., 2018). They are valid under several major assumptions, in particular a random sampling with infinitely thin beams. The newly proposed formulations are robust in a wider range of LAD values, elements size and number of beams than the usually used LAD estimators.

We recommend using the LAD estimator relying on the maximum likelihood approach because it was the less sensitive to the various sources of bias.

3.2 Voxel size and distance effects

Branch scale experiment revealed higher underestimations of LAD when voxel size increased whatever the type of vegetation or instrument. Such effect might result from heterogeneity of vegetation distribution within a given voxel. Additionally, with the phase shift instrument, raising the distance between the sensor and the measured branch yielded large overestimations, which might be related to beam divergence, which affects the effective footprint of the instrument.

Correction factors for these effects were provided for the studied species and according to voxel size. After theses corrections, we obtained LAD estimations with 20% errors compared to actual vegetation using the recommended estimator with the tested instruments (Soma et al., 2018).

3.3 Tree scale estimation

Application of the method to individual trees showed that corrections developed in previous steps produced reliable estimations providing the canopy is appropriately sampled (Fig. 1).

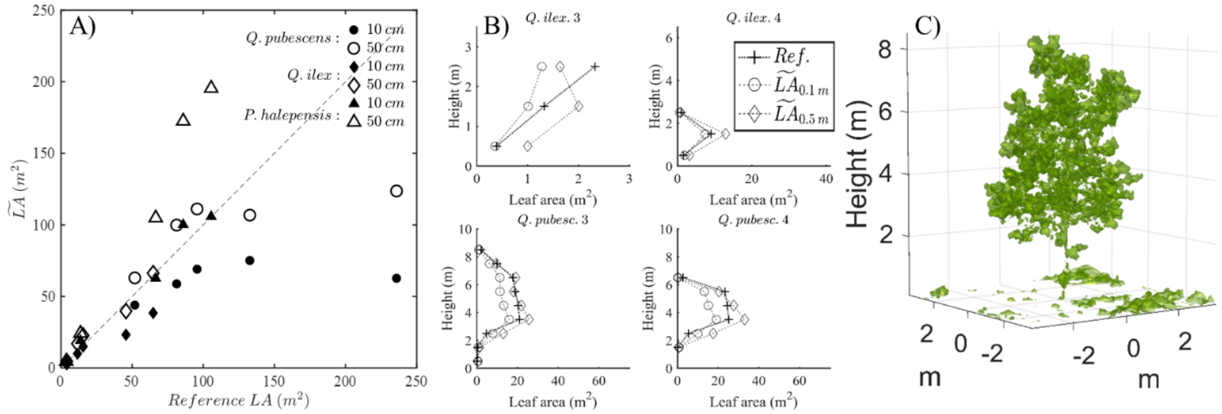

Figure 1. A) Comparison of LiDAR estimations of total tree leaf areas *versus* references for 3 species and 2 voxel sizes. B) Comparison of LAD profiles obtained from LiDAR with 0.1 m and 0.5 m voxels *versus* references. C) 3D distribution of leaf areas with 0.1 m voxel size.

3.4 Sampling limitations at plot-scale

At stand scale, the oversampling of voxels containing few vegetation compared to dense voxel negatively biased the computation of mean LAD profile. The magnitude of this bias depends on height in canopy, vegetation structure, scan design and voxel size. We found that using 0.5 m voxels was more appropriate because it eased corrections of other biases.

The developed LAD kriging method provided correct estimations in occluded voxels, and yielded better results at stand level than ignoring these areas. This method was validated in an actual forest plot.

4. Conclusions

The combination of theoretical analyses, field experiments and numerical experiments allowed to get a comprehensive understanding of processes involved in remote sensing of LAD with terrestrial LiDAR. In this study, the different sources of bias in LAD assessment were disentangled and ranked. Solutions to correct those biases at different scales, from branch to forest plots, have also been suggested.

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