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A method to estimate silhouette to total area ratio (STAR) from TLS point clouds

Daniel Schraik[1], Aarne Hovi[1], Miina Rautiainen[1,2]

[1]Aalto University, School of Engineering, Department of Built Environment, PO Box 14100, 00076 Aalto, Finland
Email: daniel.schraik@aalto.fi

[2]Aalto University, School of Electrical Engineering, Department of Electronics and Nanoengineering, Finland

1. Introduction

Correcting for clumping of needles into shoots has become a standard procedure in radiative transfer analyses of conifer forests. Clumping needs to be corrected due to the near-ubiquitous assumption of the Poisson canopy, i.e. the random distribution of plant elements throughout the canopy. While there are many ways to quantify clumping, the silhouette to total area ratio (STAR) has become the standard procedure for correction the clumping of conifer needles into shoots. STAR is the ratio of the orthogonal projection area of a body, averaged over all directions of the sphere, to its total surface area. A simple, convex body always has a STAR of ¼, whereas a composite body, such as a conifer shoot, has a STAR less than ¼. The concept of STAR originates from one of Augustin-Louis Cauchy's theorems, which was adapted for use in radiative transfer modeling of plant stands by Lang (1991).

STAR as a clumping quantifier was proven essential in accurately modeling reflectance of conifer stands (Rautiainen and Stenberg 2005). Within the concept of photon recollision probability (Knyazikhin et al. 1998, Stenberg et al. 2016), STAR can be used to quantify the photon recollision probability in a hierarchy of canopy elements, such as shoots, crowns, and stands (da Silva 2008). However, the hierarchical STAR remained a theoretical concept applicable only to simulation data due to a lack of measurement methods.

With the increasingly wide-spread use of terrestrial laser scanning (TLS) and the development of preprocessing and estimation routines for forest ecology, we have the necessary tools to develop a measurement method for STAR at the crown and stand level.

In this presentation, we present a method that is capable to estimate STAR from point cloud at any hierarchical level. We empirically validated our method with data from destructive leaf area measurements, and photogrammetric silhouette area measurements in small spruce trees.

2. Data and Methods

2.1 Estimating STAR from point cloud data

We scanned 14 spruce trees (*Picea abies* (L.) H. Karst.) from Southern Finland with a Leica P40 scanner at resolutions of 0.15 and 0.32 mrad in 2018. The scans were performed from six positions, 10 m from the tree and spread evenly across azimuth directions. We used five 4.5" Leica B&W co-registration targets for the co-registration of the point clouds. The point clouds were preprocessed in Leica Cyclone, and the point clouds were exported with the individual scan positions retained in the data to allow conversion into rays.

The point cloud data was then used to estimate the attenuation coefficient in a voxel grid covering the crowns' volumes. We used the unbiased estimator developed by Pimont et al. (2018), which is based on the modified contact frequency and accounts for biases introduced by the finite number of beams entering a voxel, and the finite size of the plant elements. The one-sided leaf area density within a voxel can then be estimated through dividing the attenuation coefficient by G, the average projection area of unit leaf area. Multiplication by the voxel volume, summing over all voxels, and doubling then yields the total (two-sided) leaf area of the tree.

The second part of STAR is the silhouette area, which we estimated from the attenuation coefficient by ray tracing, using the Beer-Lambert law to calculate attenuation as the rays traveled through each voxel. The set of all rays formed a synthetic image, where each pixel corresponded to the fraction of

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transmitted radiation in an orthogonal projection. The sum over the synthetic image, multiplied by the squared beam spacing (i.e. the pixel area) yields the silhouette area. The silhouette area was averaged over 72 directions to approximate a spherical integral.

Both above steps, estimating of attenuation coefficient (and leaf area density) and silhouette area, were carried out with voxel sizes between 5 cm and 90 cm. The measurements are described in more detail in Schraik et al. 2019.

2.2 Reference data

The total leaf area of each tree was determined destructively. We measured the trees' biomass of needles and branches up to a diameter of 2 cm. For a sample of 20 shoots per tree, we determined the leaf area, the leaf weight, and the twig weight. The fraction of leaves of the tree biomass, multiplied by the leaf area per leaf mass, yielded the total leaf area.

The directional silhouette area was determined at six directions coincident with the TLS scan locations. We used a Sony A7R camera with a 28mm lens to take photos of the trees. The photographs were taken with a white background, and were converted into binary images. Given the pixel size of the camera sensor, and the average distance between the camera and the tree crown (estimated from the point clouds), we calculated the silhouette area as the sum of the image covered by the tree.

3. Results and Discussion

Estimates for crown-level STAR were highly dependent on voxel size, and ranged from about 0.075 to 0.25. Generally, STAR estimates increased with increasing voxel size. At 90 cm voxel size, STAR was about 0.25, which can be explained simply by most trees being covered in 1 to 4 voxels, at which point the crown clumping is incorporated already into the leaf area estimates, and the resulting voxel structure can be seen as a turbid medium approximation. There seemed to be an optimal voxel size that depends on the spatial structure of the tree crown. It should be fine enough to resolve the empty space between branches, but also large enough to ensure a high number of beams inside each voxel. In our data, this voxel size seemed to be around 10 to 20 cm.

The dependence of voxel size was similar in leaf area estimates, but the trend was negative. The 90 cm voxel size resulted in estimates closest to the destructive measurements (less than 2% overestimation), whereas the 10 cm voxels overestimated leaf area by about 67%. The silhouette area estimates were less sensitive to voxel size, but exhibited a positive trend with increasing voxel size. In 10 cm voxels, silhouette area was overestimated by about 22%, while in 90 cm voxels the bias increased to about 28%.

However, it is premature to conclude that larger voxel sizes work better in leaf area estimation, because there are a number of factors at play. Soma et al. (2018) found a similar bias for small voxel sizes, but a significantly larger error in large voxels already at 70 cm in oak and pine branches. We suspect that the modified contact frequency may have a tendency to overestimate leaf area, particularly in conifer trees because the TLS footprint is too large to resolve the fine shoot structure, therefore potentially introducing a bias into estimates that is independent of the voxel size. In addition, since plant elements inside a voxel are assumed to be randomly distributed, clumping at scales smaller than the voxel size may cause a negative bias on leaf area estimates that depends on the voxel size. Together, these two biases may cancel each other out at certain voxel sizes, as we suspect was the case at 90 cm voxel size in our validation experiment.

4. Conclusions

We presented a method to quantify the silhouette to total area ratio from TLS point clouds. Our method relies on voxel-based estimates of leaf area density, which are orthogonally projected to obtain their silhouette area. As such, our method relies on the accuracy of leaf area density estimates, which is a subject of ongoing research. We validated our method using small spruce trees, which showed that the voxel size plays a crucial role in quantifying STAR as well as leaf area density. Based on our findings, we suspect that using voxel sizes between 10 and 20 cm appear to provide a reasonable trade-off between fine-scale detail and computational feasibility.

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