MEASURING LEAF ANGLE DISTRIBUTION USING TERRESTRIAL LASER SCANNING IN A EUROPEAN BEECH FOREST

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ABSTRACT

Leaf angle distribution (LAD) is an important canopy structure metric. It controls the flux of radiation, carbon and water, and has therefore been used in many radiative transfer, meteorological and hydrological models. However, LAD is too tedious to measure using conventional manual methods. Terrestrial laser scanning (TLS) has recently been proposed to estimate LAD due to its ability to record unprecedented detailed plant 3D structure. However, previous research was restricted to a controlled environment with simple canopy structure. In this research, TLS was used in a natural deciduous European beech forest to estimate LAD. Digital hemispherical photograph (DHP) was also used as a reference. The results demonstrated that both TLS and DHP could capture a variation of LAD in beech plots at different succession stages. Compared to DHP, TLS has the advantage of resolving foliar and woody materials, as well as deriving the 3D distribution of leaf angles.

***Index Terms*—** leaf angle distribution, terrestrial LiDAR, digital hemispherical photograph, forest structure, European beech

1. INTRODUCTION

Leaf angle distribution (LAD) describes the frequency of leaves orientation in different directions. It is an important component of canopy structure, which influences the flux of radiation, carbon and water. Therefore, LAD has been used as a parameter in many radiation transfer, meteorological and hydrological models. It is also a parameter required for leaf area index (LAI) estimation. However, due to challenges in its measurement, LAD is usually treated as simplified mathematical functions, e.g. spherical distribution or planophile distribution [1]. It was shown to be one of the most poorly constrained model parameters [2]. There is potential for improving models that incorporate LAD, if LAD could be more effectively quantified.

One strategy to measure LAD is to measure the orientation of individual leaves. However, manual measurement of leaf angle using an inclinometer is very tedious and difficult [3]. The enormous number of leaves require much time, while direct physical contact often leads to disturbance or damage to the leaves [3]. Consequently, the optical digital canopy photo (DCP) method has been introduced [4, 5]. First, a series of levelled DCPs were taken around the canopy at different height levels. Then leaves were identified from each photo and open source image processing software was used to measure leaf angles. Although the DCP method is robust and affordable, it involves substantial user interaction when identifying individual leaves. In addition, taking photos for trees higher than 2 m is be very difficult.

Another strategy to measure LAD is not based on individual leaves, but instead LAD is inferred indirectly from radiation measurements. Digital hemispherical photography (DHP) is one of these methods. The basic principle is to record how sunlight is attenuated by vegetation canopy in various directions. Then one can invert the Beer's Law for radiation interception to infer LAD and LAI [6]. The result of this method depends on the inversion process and could be limited by a turbid medium assumption.

With the development of terrestrial laser scanning (TLS), plant canopies could be captured with unprecedented details of the 3D structure. TLS has been used to reconstruct leaf surface and normal vectors using a plane fitting on neighboring LiDAR points [3]. But there was no leaf size constraint in [3]. Instead, fixed 6 neighboring points were employed to form each leaf surface. This may be problematic for upper canopies when point density is low. Recently, a rapid measurement of LAD method was developed based on triangulation of TLS point clouds [7]. This method demonstrated good accuracy in an isolated tree and a vineyard.

To the best of our knowledge, previous TLS research was undertaken in canopies with simple structure. No research explored a natural stand with complex forest structure. Therefore, this research aims to measure LAD using TLS in a natural deciduous forest.

2. DATA AND METHOD

2.1. Study Area and Plot Selection

The study area is the Bavarian Forest National Park, located in the southern-eastern part of Germany. The elevation ranges from 660 m to 1443 m above sea level. Dominant tree species are Norway spruce (*Picea abies*) (67%) and European beech (*Fagus sylvatica*) (24.5%) [8]. Since the orientation of needles is more difficult to define, in this research we focus only on the deciduous beech trees. In total, 36 plots were selected as shown in Fig.1, spanning from low to high elevation. These plots covered a wide range of structures. The plots were further categorized into "young, middle, mature" trees using ancillary land cover classification data.

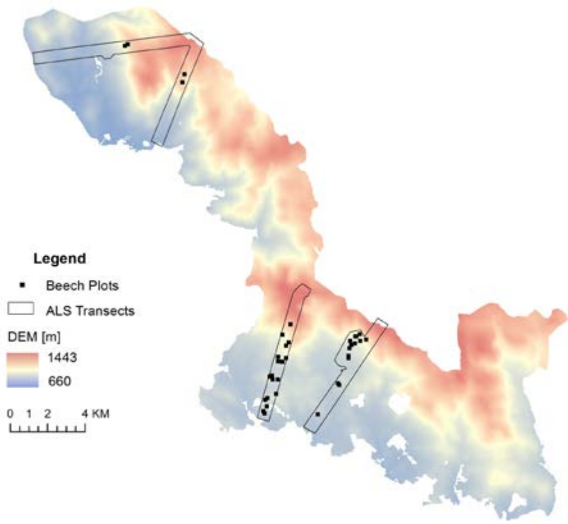

Fig.1. 36 Selected beech plots and the airborne LiDAR transects in the Bavarian Forest National Park

2.2. Data Collection

From 17-July-2017 to 9-August-2017, 36 beech plots were visited in leaf on conditions. The spatial location of each plot was measured by a differential GPS. A RIEGL VZ-400 terrestrial laser scanner was used to scan each plot. The scanner had a laser of 1550 nm wavelength, a beam divergence of 0.35 mrad, and a range accuracy of 5 mm. The angular step was set to 0.04°. In each plot, one center and three triangular scan positions were used, to reduce occlusion and increase point density. In addition to TLS data, in August 2016, four transects were also scanned by airborne LiDAR, seen in Fig.1. As a result, all 36 plots, each with a radius of 15 m was clipped from both TLS and ALS data. The ALS data was used to calculate basic plot structure metrics including mean canopy height and standard deviation of canopy height. The TLS data were used to estimate LAD.

DHP was also acquired in the fieldwork to estimate LAD as a reference. In each plot, 20 upward-pointing photos were taken by a Canon EOS 5D camera with a fish-eye lens (Sigma 8 mm F3.5 EX DF). All photos were taken on a tripod between 1 and 1.3 m above ground, in diffuse light conditions at dusk or dawn, or overcast diffuse conditions.

2.3 LAD from DHP

The basic principle to estimate LAD from DHP is based on light attenuation. Specifically, light attenuation in a direction θ can be modelled by the Beer-Lambert law,

$$P(\theta) = e^{-G(\theta)\Omega(\theta)L/cos(\theta)} \quad (1)$$

where $P(\theta)$ is the gap fraction in direction θ, $G(\theta)$ is the leaf projection function which is determined by $g(\theta)$ (LAD); L is the leaf area index; and $\Omega(\theta)$ is the clumping index. Using gap fraction measured by DHP in various directions, one can invert equation (1) to infer LAD. In this research, the automatic two-corner classification method was first applied on DHPs to classify sky and canopy pixels. Then the classified images were imported into the CanEye [9] software to calculate angular gap fraction and inversion of LAD. The exported result was the average leaf inclination angle (ALA), as shown in equation (2),

$$ALA = \frac{2}{\pi}\int_0^{\pi/2} g(\theta)\theta d\theta \quad (2)$$

where $g(\theta)$ is the LAD.

2.4. LAD from TLS

In this research, using TLS to estimate LAD is based on calculating the orientation for individual leaves. Preprocessing was first conducted on the TLS point clouds, to ensure high point density and remove noisy points. Four scans were registered into one scan using RiScan software to maximize point density. Then noisy points with deviation above 20 were filtered out according to the scanner user manual.

A major advantage of TLS to optical DHP or DCP method, is its capability to differ foliar and woody materials. By doing this, the complex mixture of leaf angle and woody material angle could be resolved. In this experiment, we followed the method in [10] to classify foliar and woody materials using combination of geometric and radiometric features. Classification accuracy were evaluated for each plot using manually selected test samples.

Then, leaf surface and woody surface were reconstructed through fitting a plane in a set of neighboring points. The radius of this neighborhood is constrained by leaf size. It was determined by consideration of tree species information and a sensitivity analysis. As a result, 4cm was used. If the total number of points within this radius was less than 3, these points would be considered isolated points and filtered out from subsequent statistical analysis. After surface reconstruction, leaf angle could be retrieved as the orientation of surface normal vector.

LAD was then calculated by histogram analysis of the zenith angles of all reconstructed leaf surfaces. In this study, it was calculated as the frequency distribution from 0° to 90° with 1° bin width. Then the average leaf angle (ALA) was also calculated, to compare with the ALA from DHP.

3. RESULTS AND DISCUSSION

Three plots were selected as representatives of European beech plots in different succession stages (young, medium, mature), using mean canopy height measures calculated from ALS data, to display their LAD results. The structural information of these three plots can be seen from Fig.2 and Table 1. Plot 027 is a quite open plot with young beech regeneration. Plot 014 is a medium beech plot with large between-crown distance and some canopy gaps. Plot 032 is a mature plot with closed canopy and few canopy gaps.

Fig.2. Aerial photos of the three European beech plots in different succession stages (young: 027; medium: 014; mature: 032)

Table.1. LAD results from DHP and TLS in three European beech plots at different succession stages

Plot	H_{mean} [m]	H_{std} [m]	ALA_{DHP} [°]	ALA_{TLS} [°]	A_{maxfre} [°]
027	5.64	6.75	56	46	41
014	15.75	4.56	49	41	33
032	26.06	3.04	26	38	23

H_{mean}: mean canopy height
Hstd: standard deviation of canopy height
ALA_{DHP}: average leaf inclination angle from DHP
ALA_{TLS}: average leaf inclination angle from TLS
A_{maxfre}: leaf angle with maximum frequency from TLS

The inclination angle of individual leaves in the three plots can be seen in Fig.3. A clear differentiation of foliar and woody materials could be observed in all three plots. In the young regeneration plot 027, there is a variety of different leaf angles, from small to larger angles (color blue to red). However, in plots 032 and 014, this can only be observed in the upper level of the canopy - in the lower level most leaves have a blue color, indicating a small leaf angle.

A quantitative comparison is demonstrated in Fig.4, LAD of plot 027 shows a continuous and symmetric distribution from 20° to 70°, indicating similar probability of leaf angle inclination in this angular range. However, LAD of plot 014 is slightly skewed towards smaller angles, with the leaf angle having maximum frequency at 33°. This skewness towards smaller angles is amplified in the mature plot 032, with the leaf angle having maximum frequency at 23°.

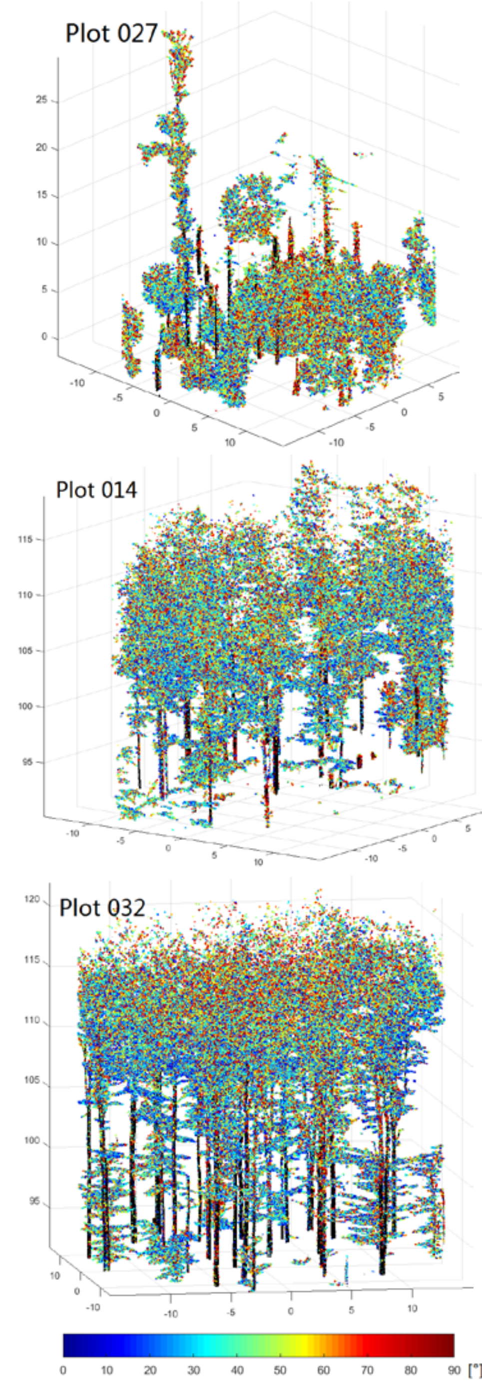

Fig.3. Leaf inclination angle (zenith angle) of three beech plots in different succession stages (Note: black points are detected woody materials)

Furthermore, LAD results from DHP and from TLS were compared to evaluate their consistency. From Table.1, both TLS and DHP could capture a tendency of decreasing average leaf inclination angle (ALA) in European beech plots from young regeneration stages to mature stages.

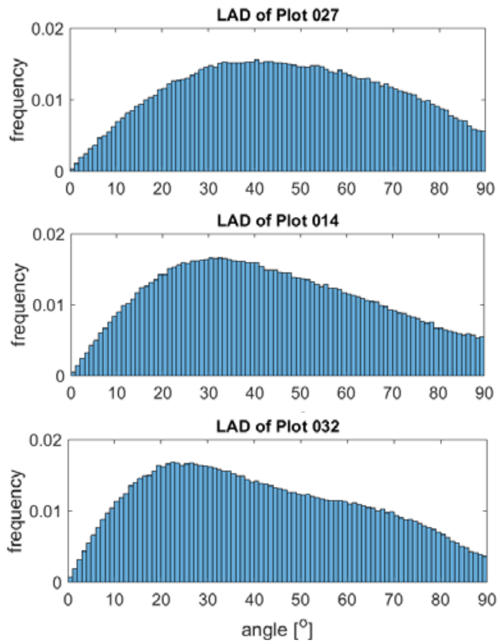

Fig.4. TLS derived leaf angle distribution (LAD) of three European beech plots in different succession stages (Note: woody materials have been excluded)

The variation of LAD in different beech plots may be explained by plant adaptation to light radiation. In the early stage regeneration plot, there is much empty space and less light competition. As a result, leaves grow in different directions with no prefered direction. But in the mature plot, leaves in the upper level are erect to reduce evapotranspiration damage from midday solar radiation, and to allow more light to reach the lower canopy [11]. Horizontal leaves in the lower level inreases light interception and leads to higher photosynthesis.

4. CONCLUSIONS

This research explored the applicability of using TLS to estimate leaf angle distribution (LAD), in a natural European beech forest. First, multi-position scanning was used to acquire very high-density point clouds of the plot. Second, foliar and woody materials were differentiated based on geometric and radiometric features. Third, the inclination of individual leaf was determined by surface reconstruction and normal vector calculation. LAD results from TLS were further compared with LAD results from DHP.

The results demonstrated TLS could estimate LAD in a natural deciduous forest with complex structure. Both TLS and DHP could capture the LAD variation in beech stands at different succession stages. Compared to DHP, TLS has the advantage to derive the inclination of individual leaf, as well as the 3D distribution of leaf angles. In addition, the angle distribution of foliar and woody materials could be resolved. Further research could focus on validating this method using DCP method and in other tree species.

5. ACKNOWLEDGMENTS

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