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Improving leaf area index (LAI) estimation by correcting for clumping and woody effects using terrestrial laser scanning

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ABSTRACT

Leaf area index (LAI) has frequently been measured in the field using traditional optical methods such as digital hemispherical photography (DHP). However, in the DHP retrieved LAI, there is always contribution of woody components due to the difficulty in distinguishing woody and foliar materials. In addition, the leaf angle distribution which strongly affects the estimation of LAI is either ignored while using the convergent angle 57.5°, or inversed simultaneously with LAI using multiple directions. Terrestrial laser scanning (TLS) provides a 3-dimensional view of the forest canopy, which we used in this study to improve LAI estimation by directly retrieving leaf angle distribution, and subsequently correcting foliage clumping and woody effects. The leaf angle distribution was retrieved by estimating the angle between the leaf normal vectors and the zenith vectors. The clumping index was obtained by using the gap size distribution method, while the woody contribution was evaluated based on an improved point classification between woody and foliar materials. Finally, the gap fraction derived from TLS was converted to effective LAI, and thence to LAI. The study was conducted for 31 forest plots including deciduous, coniferous and mixed plots in Bavarian Forest National Park. The classification accuracy was improved by approximately 10% using our method. Results showed that the clumping caused an underestimation of LAI ranging from 1.2% to 48.0%, while woody contribution led to an overestimation from 3.0% to 31.9% compared to the improved LAI. The combined error ranged from −46.2% to 32.6% of the leaf area index (LAI) measurements. The error was largely dependent on forest types. The clumping index of coniferous plots on average was lower than that of deciduous plots, whereas deciduous plots had a higher woody-to-total area ratio. The proposed method provides a more accurate estimate of LAI by eliminating clumping and woody effects, as well as the effect of leaf angle distribution.

1. Introduction

Leaf area index (LAI), defined as one-sided leaf area per unit ground surface area (Chen and Black, 1992), is one of the primary variables to characterize canopy structure (Chen et al., 1997). LAI influences many biological and physical processes, such as photosynthesis, respiration, transpiration, and light and rain interception (Asrar et al., 1984; Burstall and Harris, 1983; Chen and Cihlar, 1996). LAI plays a key role in the exchange of energy and mass between the canopy and atmosphere (Weiss et al., 2004) and is a key vegetation structure variable determining ecosystem functioning (Béland et al., 2011). Consequently it is regarded as one of the essential biodiversity variables capturing major dimensions of biodiversity change (Pettorelli et al., 2016; Skidmore et al., 2015). Therefore, an accurate and efficient estimation of LAI is of key importance for physiological, ecological and climatological studies (Li et al., 2017).

There are two main categories of methods to derive *in situ* LAI: direct and indirect ones (Jonckheere et al., 2004). Direct methods consist of leaf collection such as destructive sampling and litterfall collection, and point contact sampling (Jonckheere et al., 2004). Destructive sampling is dependent on extrapolation using allometric methods which are not easy in heterogeneous forests (Chen and Cihlar, 1995b). The use of litterfall collection is limited to deciduous forests (Neumann et al., 1989). The point contact method determines LAI from the mean

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contact number of a thin probe that passes through the canopy at a known inclination and azimuth angle (Wilson, 1960). This method requires many insertions into the canopy, which is impractical in forest stands due to the height of the trees and the high density of leaves (Chen and Cihlar, 1995b). In addition, the application of direct methods is generally laborious and time-consuming (Eschenbach and Kappen, 1996). Indirect methods using optical instruments such as LI-COR LAI-2000, TRAC or digital hemispherical photography (DHP) have been widely used for the estimates of LAI (Chen, 1996; Chen et al., 2006; Jonckheere et al., 2004; Schleppi et al. 2007). These instruments and models are less laborious and can be readily applied across larger reference sites (Leblanc et al., 2005), and also the theories behind these techniques are mature (Chen et al., 2006; Weiss et al., 2004). Among them, DHP has the advantage of providing a permanent 2-dimensional record of canopy structure (Danson et al., 2007). Various studies have used DHP as validation for gap fraction and LAI measurements (Hopkinson and Chasmer, 2009; Korhonen et al., 2011; Morsdorf et al., 2006). However, the LAI directly obtained from DHP or other optical instruments is, in fact, a plant area index (PAI) which consists of both woody and leaf components. The differentiation between the green and non-green vegetation versus the background (sky or soil) is rather unreliable, since the radiometric information from the images is affected by light and shadow conditions within a forest (Jonckheere et al., 2004). In addition, all these methods require information on the distribution of leaf angles within the canopy to estimate LAI (Jonckheere et al., 2004). Different models have been used to estimate LAI by simplifying the leaf angle distribution (e.g. spherical distribution, planophile distribution), which may introduce errors when characterizing the whole plant canopy (Ma et al., 2017a).

Terrestrial laser scanners (TLS) are capable of yielding detailed 3-dimensional canopy structure information when data are collected with a high point density (Van der Zande et al., 2011). Because TLS is an active sensor, the data can be collected without sun illumination, and the shadow can be avoided (Woodhouse et al., 2011). In addition, non-photosynthetic materials such as trunks and branches can be differentiated (Ma et al., 2016; Zheng et al., 2016; Zhu et al., 2018), so LAI is retrieved instead of PAI. A number of studies have investigated the application of TLS to estimate LAI using different methodological approaches (Danson et al., 2007; Hosoi and Omasa, 2006; Jupp et al., 2009; Moorthy et al., 2008). One group is based on voxelization of the point cloud (Béland et al., 2011; Hosoi and Omasa, 2006), another on point-based methods using data from a single scan (Danson et al., 2007; Jupp et al., 2009; Li et al., 2017). The main advantage of voxel-based methods is that no assumptions about leaf spatial distribution are required, so underestimation caused by nonrandom foliage distribution can be avoided (Hosoi and Omasa, 2006). However, voxel-based approaches are computationally expensive and convoluted by the voxel size which can significantly affect the results (Béland et al., 2014; Cifuentes et al., 2014; Li et al., 2017). In comparison, point-based approaches are more efficient by avoiding data acquisition and registration of multiple scans (Li et al., 2017).

In order to obtain LAI using point-based approaches, the penetration rate of the pulses through the canopy layer (gap fraction) needs to be converted using gap fraction theory based on the Beer-Lambert law (Nilson, 1971) as:

$$\ln(P(\theta)) = -G(\theta)LAI_e/\cos(\theta) \tag{1}$$

where $P(\theta)$ is the gap fraction at the viewing zenith angle θ, $G(\theta)$ is the fraction of the leaf area projected on a plane normal to the zenith angle θ (Ross, 2012), and $\mathrm{LAI_e}$ is effective leaf area index. $G(\theta)/\cos(\theta)$ is called the extinction coefficient, or k, which is determined by the direction of incoming beams and the foliage inclination angle distribution.

The leaf area index derived optically from gap fraction was described as "effective LAI ($\mathrm{LAI_e}$)" (Chen and Black, 1992). The conversion from $\mathrm{LAI_e}$ to LAI is needed for two main reasons: (1) the gap fraction theory for $\mathrm{LAI_e}$ estimation is based on the assumption of a random foliage distribution, (2) $\mathrm{LAI_e}$ does not account for the contribution of non-photosynthetic materials (i.e. stems, branches) (Moorthy et al., 2008). Therefore, this initial estimate of LAI needs to be corrected by taking into account the error caused by foliage clumping and the contribution of woody materials (Chen and Cihlar, 1996). Zhao et al. (2012) presented a method using TLS to retrieve the clumping index in a conifer forest which was correlated with that of hemispherical photos ($R^2 = 0.866$). Li et al. (2017) estimated the clumping index of 35 deciduous trees and achieved a strong correlation ($R^2 = 0.76$) between TLS-based LAI measurements and destructively sampled LAI measurements. Zheng et al. (2016) separated photosynthetic canopy components from non-photosynthetic active components using TLS. Their study showed that non-photosynthetic components contributed from 19% to 54% to LAI measurements depending on forest density. Zhu et al. (2018) developed a method based on the adaptive radius near-neighbor search to discriminate foliar and woody materials in a mixed natural forest. However, the influence of both foliage clumping and woody contribution on LAI measurements has not yet been explored.

This paper aims to improve the estimation of LAI from TLS in a mixed natural forest. Firstly, the leaf angle distributions of both deciduous and coniferous forests are estimated to derive the extinction coefficient k. Secondly, the clumping index Ω quantifying the effect of foliage clumping is calculated by adapting the gap size distribution method (Chen and Cihlar, 1995b) to TLS data. Lastly, the classification method (Zhu et al., 2018) was further improved by adding an additional feature (viz. zenith angle) to obtain the woody-to-total area ratio.

2. Materials and methods

2.1. Study area

The study area is located in the Bavarian Forest National Park (BFNP) in southeastern Germany. The natural forest ecosystems of the BFNP vary according to altitude: there are spruce forests on peat bogs and cold depressions in the valleys, mixed mountain forests on the hillsides and mountain spruce forests in the high elevations (Heurich et al., 2010). Data from DHP and TLS were acquired in July 2016 for 31 plots consisting of 8 European beech *(Fagus sylvatica)* plots, 8 Norway spruce (*Picea abies*) plots and 15 mixed plots (Fig. 1). The land cover map with the classification of the deciduous, coniferous and mixed forest was provided by the BFNP (Silveyra Gonzalez et al., 2018).

At least 4 hemispherical photos in each plot at the height of 1.3 m were taken and processed using the Hemisfer software (Hemisfer, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Switzerland, 2016). At the zenith angle of 57.5°, the relationship between LAI and gap fraction becomes insensitive to the leaf angle distribution (Wilson, 1960). Hemispherical photos were stratified into 5 rings with a step of 13° so that the zenith of 57.5° was close to the midpoint of ring 5 (52°-65°). An automatic thresholding method was applied using the algorithm of Nobis and Hunziker (2005) after a gamma correction ($\gamma = 2.2$) (Moeser et al., 2014). The gap fraction was calculated as the proportion of sky pixels to total pixels within analysis rings, and $\mathrm{LAI_e}$ was derived from the gap fraction based on a constant extinction coefficient (Lang, 1987). The gap size distribution method (Chen and Cihlar, 1995b) was applied to estimate the clumping index (Ω) and the corrected value of LAI (Thimonier et al., 2010). DHP measurements were used as a comparison in this paper, although they do not necessarily represent the 'ground truth'.

2.2. Terrestrial laser scanning data

The terrestrial laser scanner RIEGL VZ-400 (RIEGL Laser Measurement Systems, Horn, Austria) is a time-of-flight scanner. It is equipped with a shortwave infrared (1550 nm) laser. The laser beam