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Estimating the leaf area of an individual tree in urban areas using terrestrial laser scanner and path length distribution model

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ABSTRACT

Urban leaf area measurement is crucial to properly determining the effect of urban trees on micro-climate regulation, heat island effect, building cooling, air quality improvement, and ozone formation. Previous works on the leaf area measurement have mainly focused on the stand level, although the presence of individual trees is more common than forests in urban areas. The only feasible ways for an operational non-destructive leaf area measurement, namely, optical indirect methods, are mostly limited in urban areas because light path is constantly intercepted by surrounding buildings or other objects. A terrestrial laser scanner (TLS), which can extract an individual tree by using its unique distance information, provides a possibility for indirectly measuring the leaf area index (LAI) in urban areas. However, indirect LAI measurement theory, which uses the cosine of an observation zenith angle for path-length correction, is incompatible for an individual tree because the representative projected area of LAI changes while the observation zenith angle changes, thus making the results incomparable and ambiguous. Therefore, we modified a path length distribution model for the leaf area measurement of an individual tree by replacing the traditional cosine path length correction for a continuous canopy with real path length distribution. We reconstructed the tree crown envelope from a TLS point cloud and calculated a real path length distribution through laser pulse-envelope intersections. Consequently, leaf area density was separated from the path length distribution model for leaf area calculation. Comparisons with reference measurement for an individual tree showed that the TLS-derived leaf area using the path length distribution is insensitive to the scanning resolution and agrees well with an allometric measurement with an overestimation from 5 m^2 to 18 m^2 (3–10%, respectively). Results from different stations are globally consistent, and using a weighted mean for different stations by sample numbers further improves the universality and efficiency of the proposed method. Further automation of the proposed method can facilitate a rapid and operational leaf area extraction of an individual tree for urban climate modeling.

0. Introduction

Leaf area parameters, generally expressed as leaf area index (LAI) and leaf area density (LAD, also referred as foliage area volume density, FAVD), are important parameters for describing a canopy and crown structure given their close relation to many biological and physical processes, such as photosynthesis, respiration, transpiration, and carbon and nutrient cycling (Chen and Cihlar, 1996; Jupp et al., 2009; Ren et al., 2013; Tian et al., 2015). Urban leaf area has increasingly attracted attention considering its important role in micro-climate regulation, heat island effect mitigation, building cooling (reducing energy consumption), air quality improvement, and ozone formation (Alonzo et al., 2015; Benjamin and Winer, 1998; Najjar et al., 2015; Peper and McPherson, 1998; Simpson, 1998). Accurate leaf area measurement for urban trees is required to properly determine their benefits.

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Previous works on leaf area measurement have mainly focused on the stand level, that is, a contiguous community of trees (Leblanc and Fournier, 2014; Nowak et al., 2008; Strahler et al., 2008; Weiss et al., 2004). The leaf area measurement for an individual tree is rarely explored although isolated trees are more common than forests in urban areas. Methods for ground leaf area measurement can be classified as direct and indirect. Direct methods, such as harvesting, allometry, and litter collection, can be used for measuring an individual tree and are considered more accurate than the indirect methods (Colaizzi et al., 2017; Daughtry, 1990; Peper and McPherson, 2003; Simioni et al., 2004). However, these methods exert disadvantages, such as time-consuming, labor-intensive, and destructive to vegetation and thus are unable to complete long-term monitoring of spatial and temporal dynamics of leaf area development (Jonckheere et al., 2004). Indirect methods, in which the leaf area is inferred from measurements of other variables, such as gap probability or light transmission through canopies, are efficient, nondestructive, and amendable to automation; thus, these methods are extensively used (Macfarlane et al., 2014; Mu et al., 2017; Ryu et al., 2010; Yao et al., 2011). Most indirect methods rely on optical instruments, such as LAI-2000, TRAC, and HemiView (Chen, 1996; Leblanc et al., 2005). However, these instruments are inapplicable to urban individual tree LAI measurement because their light paths are constantly intercepted by surrounding buildings or other objects. Therefore, new instruments and methods to separate individual trees from the urban environment must be explored.

Light detection and ranging (LiDAR) is an active remote-sensing technology, which captures three-dimensional (3D) point clouds of the scanned object, thereby providing an opportunity to extract the 3D geometry of an individual tree. This technology has been extensively used in obtaining the parameters, such as tree height, diameter at breast height (DBH), canopy density, and biomass, of canopies and crowns (Bouvier et al., 2015; Koch et al., 2006; Wang et al., 2009). Moreover, a terrestrial laser scanner (TLS), which is used in measuring vegetation structure information, has advantages, such as favorable directivity, high angular resolution, and strong anti-interference capability. Another advantage of the TLS for individual tree measurement is its capability to separate the studied tree from the urban environment using its unique distance information. Three methods, namely, regression-, voxel-, and gap probability-based, have been implemented using the TLS to obtain the leaf area of an individual tree. The regression-based method is used to estimate an individual tree leaf area on the basis of a regression model with LiDAR-derived tree dimensions, such as tree height and crown diameter (Roberts et al., 2003). This method is less laborious and more efficient than the traditional allometric method because this method uses LiDAR-derived tree dimensions rather than manually measuring the tree dimensions for regression. However, the regression-based method still relies on manually measuring the leaf area of several trees to establish a regression relationship, and the accuracy of this method is largely limited by the accuracy of the LiDAR-based estimates of crown dimensions (Roberts et al., 2005). The voxel-based 3D modeling method is used to estimate the LAI and leaf area density by directly counting the contact frequency in each layer of the studied tree (Beland et al., 2014; Grau et al., 2017; Hosoi and Omasa, 2006). This method is non-destructive but inappropriate for measuring multiple trees given its requirement for fully and evenly scanned data from several stations for every tree. The gap probability-based method is used to calculate the LAI from the gap probability or gap size distribution based on Beer's law. This method is explored further than the other methods given its developed theory and operational and efficient measurement scheme for continuous canopies (Chianucci et al., 2015; Lin and West, 2016; Moorthy et al., 2008; Xie et al., 2017). However, most gap probability-based methods at the stand level require an adjustment in terms of the individual tree because the continuous canopy assumption is typically unsatisfied. Two theoretical problems in Beer's law for individual tree measurement are presented as follows: (1) the representative projected area changes with the change in an observation zenith angle (Nilson, 1999) and (2) a large proportion of laser pulses are distributed in large zenith angles near 90° considering the relative position and height between the TLS station and the tree crown, which can hardly be used in the traditional methods (Demarez et al., 2008; Gonsamo and Pellikka, 2009). Moreover, the 3D LiDAR data are not fully explored in the gap probability-based method because the gap probability or gap size distribution used in these methods only has 2D information.

A path length distribution model (known as the PATH method) is a Beer's law-based method, which considers various path lengths within the crowns (Hu et al., 2014) and has a potential for using the 3D information of LiDAR, that is, distance (Hu et al., 2018). The path length distribution model is not limited by the observation zenith angle because this model replaces the traditional cosine path-length correction for a continuous canopy with a real path length distribution. This model is originally used to measure the LAI of the continuous canopy and derives the relative path length distribution from the gap probability distribution using a sliding window (Hu et al., 2016; Yan et al., 2016; Zeng et al., 2015). The unique distance information of the LiDAR provides a potential to obtain the accurate path length information directly for the path length distribution model, thereby possibly separating the path length and leaf area density. Moreover, the model can also be used to eliminate the influence of the laser pulses reflected by the objects rather than the target tree. Owing to these findings, the proposed method adjusted the path length distribution model to an individual tree to calculate the leaf area density and leaf area by building an envelope using the LiDAR data to obtain the absolute path length.

1. Modeling the leaf area of a single tree

1.1. Beer's law for a forest stand

The general formula of the Beer's law-based method is developed for a forest stand as follows:

$$P(\theta) = e^{G(\theta)\cdot LAI/\cos\theta} \tag{1}$$

where $P(\theta)$ is the gap probability in the observation zenith angle θ, $G(\theta)$ is the leaf projection coefficient, and $\cos(\theta)$ is used for considering the path length.

We assume that the height is H, the path length that passes through the stand is $H/\cos(\theta)$, and its representative projected area is $H\cdot\tan(\theta)$ (Fig. 1a) (Nilson, 1999). For a forest stand, the LAIs calculated in different zenith angles are comparable and compatible because the canopy is continuous, although the representative projected areas in different zenith angles are different. The leaf area per unit ground calculated in different zenith angles can be regarded as similar because the leaf area increases with the representative projected area. The measurement of different zenith angles can be regarded as different samples that represent the stand. Notably, the continuous canopy is an assumption in nearly all indirect LAI measurement methods, including the traditional clumping correction, because all of these methods use Eq. (1) or $\cos(\theta)$ for path-length correction.

1.2. Beer's law for a single tree

However, the LAIs calculated using Eq. (1) in different zenith angles for a single tree are incomparable and incompatible because the representative projected area changes, whereas the total leaf area remains unchanged (Fig. 1b). Therefore, these LAIs are ambiguous and cannot be averaged directly.

The use of leaf area density is suggested because the LAI of an individual tree is ambiguous, unless the size and position of the ground area are also provided (Li-COR, 2011). However, the leaf area density alone remains insufficient for characterizing a tree crown because its leaf area still varies within the volume. The total leaf area may be the optimum variable to characterize an individual tree because the area is