Agricultural and Forest Meteorology 236 (2017) 1–21

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Retrieving forest canopy extinction coefficient from terrestrial and airborne lidar

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ARTICLE INFO

Article history:
Received 8 May 2016
Received in revised form 2 January 2017
Accepted 4 January 2017
Available online 18 January 2017

Keywords:
Lidar data
Extinction coefficient
Foliage inclination angle
Foliage azimuthal angle

ABSTRACT

Accurately retrieving the extinction coefficient (k) of foliage elements is a key step to spatially mapping the radiation regime within and under a forest canopy. The azimuthal angle of foliage elements (characterized by their normal vectors) is an important factor for improving the retrieval accuracy of k using 3-D voxels derived from lidar data. In this work, we first developed and validated an approach to retrieve k for a forest canopy by considering both inclination and azimuthal angles from terrestrial laser scanning (TLS) data. Then, we explored the feasibility of applying the proposed method to aerial laser scanning (ALS) data through four point thinning experiments for both broadleaf and coniferous trees. Our results showed that: (1) TLS-based foliage orientation could capture 86% ($N = 209$, $p < 0.001$) and 64% ($N = 78$, $p < 0.001$) of the variance in manually measured azimuthal and inclination angles, respectively for an artificial broadleaf tree; (2) the proposed lidar-based k retrieval method can be applied to both ALS- and TLS- based forest lidar data; and (3) the azimuthal angle of foliage elements is an important factor for retrieving k of a forest canopy, and both TLS and ALS platforms have differing effects on the estimates of forest k. Using this new framework, we were able to use lidar data to model the expected spatio-temporal distribution of photosynthetically active radiation within forest canopies.

1. Introduction

Characterizing the light environment within a forest canopy is fundamental for understanding the spatial variability of physiological and ecological processes such as photosynthesis (Niinemets, 2007; Niinemets, 2010), respiration (Suwa and Hagihara, 2008; Way et al., 2015), and evapotranspiration (Barrett et al., 1996; Duchemin et al., 2006; Zenone et al., 2015). Along the transmission path of incoming solar beams, photons interact with canopy elements through absorption, penetration and scattering (Black et al., 1991; Van der Zande et al., 2011). The fate of photosynthetically active radiation (PAR) upon reaching a forest canopy is threefold: absorption, reflection, and transmission. Quantifying the fates of canopy penetrating photons, and how they regulate forest energy exchange is vital for understanding the processes driving vegetation response to environmental conditions at a range of scales (Niinemets, 2010).

Forest canopy extinction coefficient (k) is a key indicator of the interception efficiency of light penetrating through a forest canopy as light intensity gradually decreases due to repeated attenuation by foliage elements (Campbell, 1986; Monsi and Saeki, 1953), and it is usually computed as (Eq.(1)):

$$k(\theta_s, \varphi_s) = G(\theta_s, \varphi_s)/\cos(\theta_s) \quad (1)$$

Where θ_s and φ_s represents zenith and azimuthal angles of beam direction, and $G(\theta_s, \varphi_s)$ is the mean projection of unit leaf area on the plane perpendicular to beam direction (Monsi and Saeki, 1953). However, this approach is usually based on the assumption that the azimuthal angles of foliage elements are randomly distributed (Campbell, 1986). K is an important input parameter for radiative transfer models (Myneni et al., 1989) and widely used for estimating effective leaf area index (LAIe) based on the probability of light

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http://dx.doi.org/10.1016/j.agrformet.2017.01.004
0168-1923/

penetrating through a forest canopy (Chen, 1996; Magney et al., 2016). The value of *k* is determined both by the direction of incoming solar beams and orientation of foliage elements – including both inclination and azimuthal angles.

For simplification purposes, approximations (i.e., 0.5 and 0.58) (Hirata et al., 2007; Richardson et al., 2009) or constant values (Zhang et al., 2014) of *k* are often used. However, this simplification process will introduce errors when trying to characterize the spatial and temporal distribution of radiation throughout plant canopies (Aubin et al., 2000; Propastin and Panferov, 2013), leaf area index (LAI) estimates (Poblete-Echeverria et al., 2015; Saitoh et al., 2012), and the absorption of photosynthetically active radiation (Forrester et al., 2014).

The inherent complexity of forest canopies makes it difficult to manually retrieve *k*. Usually, the method used for *k* retrieval is based on the numerical deduction method (Eq.(1)) (Nilson, 1971; Ross, 1981b), where the *k* value for a given incoming direction of solar beams can be calculated by characterizing the orientation distribution of foliage elements using the G-function (i.e., mean projection coefficient). Different models have been developed to compute the G-function by approximating foliage orientation probability distribution elements based on geometric objects such as a cone, sphere, cylinder, and/or ellipsoid (Campbell, 1990; Monteith and Unsworth, 1990). In addition, parameter-based models such as Wit's function model (de Wit, 1965) and the Beta function (Goel and Strebel, 1984) were developed for calculating the value of k. However, all of these models have assumed that the azimuthal angles of foliage elements were randomly distributed, which is not always true (Cescatti, 1997; Chen and Cihlar, 1995).

Both photosynthetic and non-photosynthetic canopy components effectively intercept incoming parallel solar beams penetrating through a forest canopy. Thus, all foliage elements (i.e., leaves, flowers, branches, and stems) should be considered during the calculation of G-function and *k* (Suwa, 2011). However, many studies only considered the effects of photosynthetic canopy components (i.e., leaves) when estimating light interception (Clough et al., 1997; Suwa and Hagihara, 2008). To find the foliage elements' orientation distribution, manual-based methods have been used (Lang, 1973). However, they are usually very time-consuming and labor intensive. A suitable alternative to manual measurements can be the use of discrete light detection and ranging (lidar) data generated using either aerial laser scanning (ALS) or terrestrial laser scanning (TLS). Lidar data of a forest stand implicitly contain the three dimensional (3-D) structural information of forest canopies, and had been used to determine leaf orientation (Eitel et al., 2010; Zhao et al., 2015; Zheng and Moskal, 2012b). The inherent differences between ALS and TLS platforms result in different point densities and the level of detail (LOD) of forest canopies, making it important to distinguish between the two when developing retrieval techniques for parameters such as *k*.

Traditional characterization of forest canopy structure can be classified in several different ways: (1) Homogeneous turbid medium phase: all foliage elements are randomly distributed within forest canopies (Lang and McMurtrie, 1992; Ross, 1981a); (2) Geometric shapes with turbid medium: the tree crowns are approximated by different geometric objects such as cone and ellipsoid, and the foliage elements were distributed within the crown shape as turbid medium (Li and Strahler, 1986); (3) Clumping effects phase: a parameter called the "clumping index" (Chen and Black, 1992) was introduced to modify the Beer's law to approximate the real forest stand structure considering the clumping effects among the foliage elements; (4) Geometric shapes with clumping leaves or needles: the clumping effects of needles are characterized by clumping index within a tree crown approximated by different geometric objects (Chen and Leblanc, 1997; Mõttus and Sulev, 2006); (5) True forest canopy structure phase: new technology such as lidar permits acquisition of the 3-D spatial distribution of foliage elements of a forest canopy. The spatial distribution of the radiation regime in 3-D space is determined by both the geometric and optical properties of foliage elements (Ross, 1981a). The geometric properties of a foliage elements include the size, shape, and orientation of leaves – including inclination, azimuthal angles, and spatial configuration of leaves. To accomplish this, 'voxels' (volume elements) are derived from a lidar dataset and have been used to obtain forest structural parameters (Hosoi and Omasa, 2006; Popescu and Zhao, 2008; Zheng et al., 2016b; Zheng and Moskal, 2012a), and investigate the spatial distribution of crown radiation regime (Magney et al., 2016; Van der Zande et al., 2011). However, the point density of lidar data and the increasing laser spot size resulting from laser beam divergence will determine the LOD of captured forest canopies, and will further affect the estimation of *k* within a forest canopy. Additionally, the effects of point density on the estimates of *k* are still not clear. For these reasons, the overarching objective of this study was to retrieve forest canopy *k* from 3-D lidar data. Our specific objectives were to:

1) develop and validate a novel approach to quantitatively characterize foliage orientation (both the inclination and azimuthal angles) based on TLS-based lidar data;
2) propose a method to estimate the forest canopy G and *k* values applicable to both TLS- and ALS-based 3-D lidar data; and
3) Investigate the effects of point density, forest types, and laser sampling approaches on final accuracy of *k* using both ALS and TLS data.

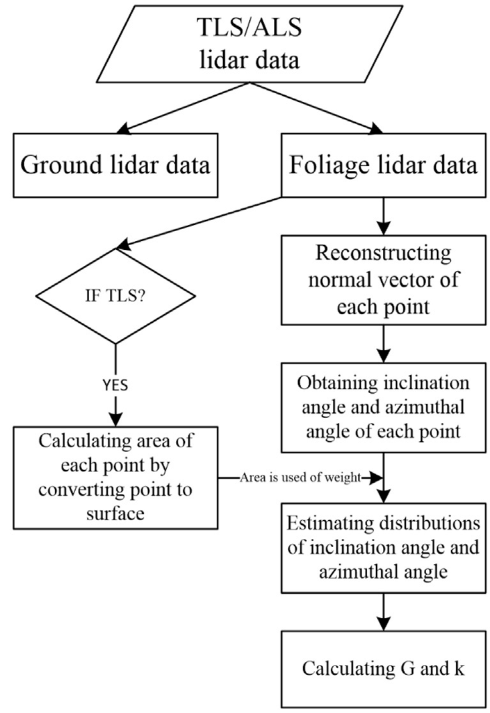

Fig. 1. The flow chart of calculating the mean projection coefficient (i.e., G-function) and extinction coefficient (*k*) based on the raw TLS or ALS lidar data.

2. Material and methods

The general flowchart of retrieving the *k* based on the 3-D lidar data generated from either TLS or ALS has been shown in Fig. 1.