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Retrieving forest canopy clumping index using terrestrial laser scanning data

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ABSTRACT

Quantitatively characterizing the non-random spatial distributions of foliage elements including coniferous needles is critical to map the radiation regime and retrieve the biophysical parameters of a given forest canopy from three-dimensional (3-D) perspective. Different experimental setups bring various challenges to the process of retrieving forest canopy clumping index (CI) using terrestrial laser scanning (TLS). In this paper, through developing a voxel-based gap size (VGS) algorithm, we compared the TLS-based forest canopy CIs with the ones obtained using the digital hemispherical photography (DHP)-based and tracing radiation and architecture of canopy (TRAC)-based approaches. Moreover, we investigated the effects of incident directions of solar beams, voxel size, and woody canopy components on the final retrieval accuracy of forest canopy CIs. Our results showed that: (1) TLS-based CIs accounted for 81% ($N = 30, p < 0.001$) of variations in the DHP-based method. (2) the anisotropic nature of forest canopy CIs suggested that a relatively comprehensive TLS data of a forest canopy was required to investigate the 3-D spatial variations of forest gap size distributions and CIs. (3) The user-defined laser sampling spacing was a reliable reference value to determine the voxel size when using the VGS algorithm. (4) It was recommended to separate woody canopy components when computing the forest canopy CI, especially for forest plots with higher proportions of woody material. (5) The effects of the penumbra on TLS-based forest canopy CIs were much more limited compared with the traditional optical instruments (i.e., DHP or TRAC). This work provides a solid foundation to dramatically improve the retrieval accuracy of leaf area index (LAI) using TLS.

1. Introduction

Clumping index (CI) is essential to quantitatively characterize the non-random distributions of foliage elements within a forest canopy (Nilson, 1971). Accurately retrieving forest canopy CI is a crucial step to efficiently improve the retrieval accuracy of forest biophysical parameters (Breda, 2003), and understand the interactions between forest radiation regime and physiological processes in a three-dimensional (3-D) domain (Chen et al., 2016; Rochdi et al., 2006). First, forest canopy CI can be used to obtain the leaf area index (LAI) by correcting the effective LAI (LAIe), which is a crucial input parameter to various process-based ecological models (Baldocchi et al., 2002; He et al., 2012). Without considering the foliage clumping effect when using a traditional optical-based method, the LAI is typically underestimated by up to 50% (Fassnacht et al., 1994; Gower et al., 1999). Second, forest canopy CI affects physiological process such as photosynthesis (Chen et al., 1999; Walcroft et al., 2006) and evapotranspiration through altering leaf or canopy stomatal conductance (Chen et al., 2016).

The CI parameter was introduced by Nilson (1971) to modify Beer's law (Monsi and Saeki, 1953) to improve LAI estimates. The increase of forest canopy CI from 0 (i.e., strongly clumped foliage elements) to 1 (i.e., randomly distributed foliage elements) suggests a decrease in the degree of clumping effects within a forest canopy. Forest clumping effects usually occur at three different spatial scales (Breda, 2003; Chen et al., 1997). (1) Within foliage elements clumping (CI-1): many researchers used a parameter called the “needle to shoot area ratio” to characterize the clumping degrees of needles within a coniferous shoot. It is equal to one for broadleaf trees since the basic foliage element unit is a single leaf in this case. (2) Foliage elements clumping (CI-2): in a forest canopy, there are many clumped shoots and leaves around tree stems. However, many studies did not differentiate photosynthetic canopy component (i.e., leaves) and non-photosynthetic canopy components (i.e., stems and branches). (3) Tree crown clumping (CI-3): by approximating tree crowns as 3-D geometric objects (Gerard and North,

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1997; Strahler and Jupp, 1990) or two dimensional (2-D) circles with varying radii (Picard et al., 2009, 2010), it becomes possible to investigate tree spatial distribution patterns at the landscape level. Tree crowns may have regular, random, or clumped spatial distribution patterns due to non-random distributions of various resources (i.e., nutrient, water, or light) (Couteron et al., 2003; Getzin et al., 2008). The forest canopy CI-3 is beyond the scope of this study. Thus, the forest canopy CI can be computed as (Eq. (1)) (Chen, 1996):

$$\text{CI} = \text{CI-2}/\text{CI-1} \tag{1}$$

Forest canopy CI-1 is computed as the ratio of half of the total needles area in a shoot (S_a) over half of the total shoot area (S_p) (Chen, 1996; Chen and Cihlar, 1995b). S_p is obtained by approximating a shoot as a geometric object such as a cylinder. In practice, there are three different methods for computing S_a including the optical scanner-based method (Ishii and Dannoura, 2004), water volume displacement-based method (Chen et al., 1997), and destructive sample-based method (Katsuno and Hozumi, 1987). There are usually two steps to retrieve forest canopy CI-2. (1) Gap size estimation phase: gap size distributions of foliage elements can be obtained using the traditional optical instruments such as Digital hemispherical photography (DHP) and Tracing radiation and architecture of canopy (TRAC) or light detection and ranging (lidar) technology to conduct the field-based measurements (Chen and Cihlar, 1995a; Gonsamo and Pellikka, 2009). The main distinctions between the optical instruments and lidar technology are: a) working light environment: DHP requires an environment with diffuse light to separate foliage elements from the sky through setting the optimum exposure setting (Leblanc, 2004). The TRAC equipment should be operated under direct solar beams and hold by hand to walk along a line transect under a forest canopy. The recorded photosynthetic photon flux density (PPFD) gradient along the line transect allows the retrieval of forest canopy CI (Leblanc et al., 2002). There is no requirement on working light environment by lidar technique. b) sampling methods: the DHP technique captures a digital number (DN) image of a forest canopy with a hemispherical field-of-view (FOV) mode (i.e., horizontal: 0°–360°, vertical: 0°–90°) (hereafter referred to as 'hemispherical mode'). Meanwhile, the TRAC instrument records a PPFD gradient line transect under a forest canopy with a specific incident direction of solar beams. However, it is flexible to collect lidar data with either one or multi-location scanning modes. (2) CI-2 retrieval phase: There have been three well-developed and accepted methods successfully developed during the past three decades to characterize the clumping degree of foliage elements quantitatively (i.e., CI-2). First, Lang and Xiang (1986) developed a method (i.e., "LX" algorithm) to estimate the clumping index (i.e., CI-2) of foliage elements of a given line transect under a forest canopy based on a gap fraction theory. The assumption behind the "LX" algorithm was that foliage elements randomly distributed along each short transect within a given long transect, which limited its applicability due to the difficulty in determining the length of each short line transect. Second, Chen and Cihlar (1995a) proposed an approach (i.e., "CC" algorithm) to retrieve forest canopy CI-2 through analyzing the gap size distribution of each line transect based on a gap size theory. In this theory, the clumping degree can be deduced numerically by comparing the differences of gap size distributions before and after applying the gap remove process. Third, Leblanc et al. (2005) proposed a new approach (i.e., "CLX" algorithm) by combining "LX" and "CC" algorithms. The "CLX" algorithm holds the capacity to estimate the CI-2 by removing big gaps to meet the assumption that the foliage elements randomly distributed in each short transect of a given long transect. Both the "CLX" and "CC" algorithms are widely used algorithms for retrieving forest canopy CI. In the current paper, we chose the "CC" algorithm because it was the built-in theoretical foundation of TRAC and DHP instruments. Since we adopted the same algorithm (i.e., "CC" algorithm) in the second stage of forest CI retrieval, the gap size distributions obtained from various instruments mainly explained the differences of final forest canopy CIs. Besides the DHP and TRAC instruments, some other optical instruments such as a multiband vegetation imager were also developed to measure forest canopy CI-2 using visible and near-infrared paired canopy images at forest plot level (Kucharik et al., 1997; Zou et al., 2015). The well-registered upward image pairs should be taken at multiple locations of a forest plot for retrieving forest canopy CI-2 when using the multiband vegetation imager. At the regional or global scales, multi-angle optical satellite imagery data such as POLDER or MODIS have been successfully used to map the spatial distribution of forest canopy CI (Chen et al., 2005; Zhu et al., 2012). For example, Chen et al. (2005) mapped global forest canopy CI by combining the POLDER satellite data and a geometric optical model.

In recent years, lidar technology, especially terrestrial laser scanning (TLS) has become a powerful tool for retrieving 3-D forest canopy structural parameters (Eitel et al., 2016; Zhao et al., 2012; Zheng and Moskal, 2012). Forest gap fractions were estimated based on either the laser return intensity (Strahler et al., 2008; Zhao et al., 2012) or point density using voxel-based methods (Cifuentes et al., 2014; Zheng et al., 2017; Zheng et al., 2016). The LAIe can then be further obtained based on the estimated gap fraction using Beer's Law (Monsi and Saeki, 1953). Some TLS-based methodologies have also been proposed to achieve the 3-D leaf area density of a forest canopy using voxel-based methods (Béland et al., 2014; Grau et al., 2017), and most of these methods assumed that the points randomly distributed within fixed-size voxels. However, it is usually difficult to determine the optimum voxel size affected by the characteristic size of a leaf, distances between target objects and TLS sensors, and vegetation density (Grau et al., 2017). Besides, some researchers attempted to develop point-based LAI retrieval methods based on the TLS data without using the Beer's law (Ma et al., 2016a; Olsoy et al., 2016; Yun et al., 2016). However, most of the point-based LAI retrieval methods were limited to individual tree scale due to the strict requirements of the high-density and comprehensive TLS data. Quantitatively characterizing the clumping effect of foliage elements using 3-D TLS data has become a pivotal step to converting LAIe to LAI. The current lidar-based methods for retrieving forest canopy CI fall into two different categories: (1) statistically-based method: retrieves forest canopy CI based on an empirical relationship between aerial laser scanning metrics and field-based CI measurements (Thomas et al., 2011). (2) physically-based method: combines lidar data with a physical-based approach such as the "LX," "CC," or "CLX" algorithm to retrieve forest canopy CI-2 (García et al., 2015; Zhao et al., 2012).

Due to the various TLS experimental settings, the methods for processing its data should be carefully chosen accordingly. Usually, a single point processing technique is not always suitable for analyzing various TLS data with different representations of a forest canopy. A directional (i.e., either horizontal or vertical) point cloud slicing method is usually not applicable in processing a single location-based TLS forest lidar data due to the incomplete forest canopy representation. On the other hand, a simple point cloud slicing method (i.e., either horizontal or vertical) is insufficient for retrieving forest canopy CIs due to its anisotropic nature (Law et al., 2001; Pisek et al., 2013). For example, Zhao et al. (2012) and Li et al. (2017) retrieved the foliage canopy CI-2 along azimuthal directions of TLS data generated at one central location. García et al. (2015) retrieved forest canopy CI-2 by horizontally slicing the TLS data obtained from multi-location for specific zenith angle ranges, and the optimum voxel sizes were decided by comparing the TLS- and DHP-based results. Moorthy et al. (2008, 2011) obtained forest canopy CI-2 in a vertically sliced plane based on a multi-location forest TLS data. However, the TLS-based forest canopy CI results processed using a specific slicing method can only be compared with the field-based CIs produced using the similar processing method. For example, the TLS-based forest canopy CIs processed using horizontal or vertical point cloud slicing methods should not be compared with the CIs obtained using the DHP-based method.

A relatively comprehensive forest lidar dataset is needed when