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Retrieval of effective leaf area index (LAIe) and leaf area density (LAD) profile at individual tree level using high density multi-return airborne LiDAR

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ABSTRACT

As an important canopy structure indicator, leaf area index (LAI) proved to be of considerable implications for forest ecosystem and ecological studies, and efficient techniques for accurate LAI acquisitions have long been highlighted. Airborne light detection and ranging (LiDAR), often termed as airborne laser scanning (ALS), once was extensively investigated for this task but showed limited performance due to its low sampling density. Now, ALS systems exhibit more competing capacities such as high density and multi-return sampling, and hence, people began to ask the questions like—"can ALS now work better on the task of LAI prediction?" As a re-examination, this study investigated the feasibility of LAI retrievals at the individual tree level based on high density and multi-return ALS, by directly considering the vertical distributions of laser points lying within each tree crown instead of by proposing feature variables such as quantiles involving laser point distribution modes at the plot level. The examination was operated in the case of four tree species (i.e. *Picea abies*, *Pinus sylvestris*, *Populus tremula* and *Quercus robur*) in a mixed forest, with their LAI-related reference data collected by using static terrestrial laser scanning (TLS). In light of the differences between ALS- and TLS-based LAI characterizations, the methods of voxelization of 3D scattered laser points, effective LAI (LAIe) that does not distinguish branches from canopies and unified cumulative LAI (ucLAI) that is often used to characterize the vertical profiles of crown leaf area densities (LADs) was used; then, the relationships between the ALS- and TLS-derived LAIes were determined, and so did ucLAIs. Tests indicated that the tree-level LAIes for the four tree species can be estimated based on the used airborne LiDAR (R^2 = 0.07, 0.26, 0.43 and 0.21, respectively) and their ucLAIs can also be derived. Overall, this study has validated the usage of the contemporary high density multi-return airborne LiDARs for LAIe and LAD profile retrievals at the individual tree level, and the contribution are of high potential for advancing forest ecosystem modeling and ecological understanding.

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1. Introduction

As a representative biophysical parameter for characterizing canopy structure, leaf area index (LAI) has kept attracting considerable attention (Watson, 1947; Chen and Black, 1992; Breda, 2003). Its popularity is rooted in its concise definition, i.e., total one-sided green leaf area per unit ground surface area (Watson, 1947; Chen and Black, 1992). Its significance is evidenced by its numerous application cases both in the studies of forest ecological processes, such as evapotranspiration (Chen et al., 2005), precipitation interception (Dietz et al., 2006), carbon and water cycling (Dufrene et al., 2005) and primary production (Cleugh et al., 2007; Duursma et al., 2009), and in the developments and applications of forest ecosystem models, such as the leaf population probabilistic canopy dynamics model (SLCD) at the regional scale (Sainte-Marie et al., 2014) and the organizing carbon and hydrology in dynamic ecosystems environment model (ORCHIDEE) at the global scale (Yue et al., 2013). These endeavors all suggested that tree LAI servers as a key variable for accurate prediction of forest dynamics, and accurate retrieval of tree LAIs is of fundamental implications for forest ecosystems and ecological studies.

1.1. Literature review

The efficient techniques for accurate LAI derivations have kept being developed. A large variety of methods based on field sam-

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pling and remote sensing (RS) have been proposed and validated, as summarized in the relevant reviews (Jonckheere et al., 2004; Weiss et al., 2004; Zheng and Moskal, 2009). Along with the technical progress on tree leaf measurements, the definition of LAI and the principle of its acquisition have undergone a series of "evolutions", from measuring foliage area index by adopting the method of point quadrat analysis (Wilson, 1959), estimating effective LAI (LAIe) by pushing forward a Poisson-model-based method (Wilson, 1960) to converting LAIe to true LAI by introducing a leaf clumping index (Nilson, 1971). Later, a Poisson theoretical model was advanced to handle the clumping effect caused by branch architecture (Chen and Black, 1991), and two gap-size theories were also adopted to deal with another overlapping effect involving canopy architecture (Chen and Cihlar, 1995). Recently, the effects of soil type and plant architecture (Darvishzadeh et al., 2008) and tree seasonal growth (Croft et al., 2014) on LAI estimations were investigated.

Aiming at the diverse LAI forms as mentioned above, a lot of endeavors attempted and validated different RS techniques to implement their retrievals. These solutions cover most of the conventional RS means, such as Landsat thematic mapper (TM) imaging (Chen and Cihlar, 1996; Anderson et al., 2004) and enhanced TM plus (ETM+) imaging (Berterretche et al., 2005), airplane imaging (Anderson et al., 2004), multi-angular imaging (Casa and Jones, 2005), high-resolution satellite imaging (Chen et al., 2002; Pu and Cheng, 2015), shortwave infrared imaging (Brown et al., 2000), multispectral imaging (Madugundu et al., 2008) and microwave Radar (Brakke et al., 1981). Most of these works were conducted based on passive optical RS, meanwhile it was also realized that problems may occur in the process of passive optical RS-based LAI retrievals. For example, one of such problems is the phenomenon of index saturation for large LAIs (Anderson et al., 2004). Specifically, LAI retrievals often get saturated when the surface vegetation covers reach a high level. This problem can be handled by directly acquiring information about tree or forest 3D structures. But for individual trees typically with complicated structures, the common method of 3D object reconstruction based on optical image-pairs, which follows the generic principle of photogrammetry, often cannot work well on supplying tree structural information (Lisein et al., 2013).

To the end of tree structure acquisition, the RS technique of light detection and ranging (LiDAR) can serve as a solution. Airborne LiDAR, also referred to as airborne laser scanning (ALS), has been attempted for LAI retrievals. Earlier, ALS was applied for exploiting canopy structural and biophysical attributes (Lefsky et al., 1999). Then, ALS was used to derive LAIs and canopy gap fractions in forest stands of different tree species (Lovell et al., 2003; Lim et al., 2003; Riano et al., 2004; Houldcroft et al., 2005). In addition to those often-used discrete return ALS systems, full-waveform (FWF) airborne LiDAR has also been applied for the task of estimating forest fractional covers (Morsdorf et al., 2006). However, in subject to relatively low sampling densities, the common ALS systems produced in the last decade cannot support the advancement of LAI retrieval into the stage of higher accuracies. Hence, in the field of LiDAR-based tree LAI retrievals, the emphasis transferred from airborne LiDAR to static terrestrial LiDAR (also termed as static terrestrial laser scanning, TLS) approximately from the mid-term of last decade, and this trend continues till now.

With the strength of acquiring high density point clouds that are appropriate for 3D tree representations, TLS recently has been enthusiastically attempted for precisely deriving LAIs. The studies of TLS-based LAI retrievals started from a work on TLS-based investigation of canopy gap fractions (Lovell et al., 2003). Then, the study explicitly on TLS-based leaf area density (LAD) and LAI estimations was conducted by converting point clouds into 3D voxels (Hosoi and Omasa, 2006), and the factors possibly influencing the performance of the woody canopy LAD profile estimations were also investigated (Hosoi and Omasa, 2007). From the perspective of optimizing instrument setting and measurement designing, a waveform model was developed to help TLS to play its full role in LAI estimations (Koetz et al., 2006). The following studies found that the laser occlusion effect by tree crowns led to TLS-based LAI predictions with underestimated LADs at their upper layers (Clawges et al., 2007). Further, it was realized that other factors such as the distribution of leaf inclination angles, the number of incident laser beams and the laser extinction coefficient can also influence the prediction efficacy (Takeda et al., 2008). To address these influences, a geometrical-projection-based directional gap fraction estimation method was proposed (Danson et al., 2007). The FWF TLS capable of somehow handling the occulsion effect was used for LAI estimations (Strahler et al., 2008; Zhao et al., 2011). A more comprehensive computational-geometry-based approach recently was developed for TLS-based LAIe derivations (Zheng et al., 2013), and the effect of TLS spatial variability on LAI retrievals was explored (Zheng and Moskal, 2012). Based on all of these endeavors, it is becoming accepted that TLS can serve as an efficient solution equivalent to the typical digital-hemispherical-photography-based method (Lovell et al., 2003), for tree LAI measurements and, even, as an appropriate way of collecting the ground-truth data to calibrate the passive optical RS- and ALS-derived tree LAI values (Zheng et al., 2013; Hopkinson et al., 2013).

1.2. Technical gap

Although TLS proved to be available for accurate retrievals of tree-level LAIs and LAD profiles, its applications are restricted to its limited coverage. In fact, as regards to tree LAI retrievals that generally prefer the two conditions of fine-scale and large-area being satisfied simultaneously, airborne LiDAR that in fact was attempted for LAI retrieval earlier than TLS has kept being investigated for this task in the past ten years. The assumed specific measures can be divided into two categories. The schematic plan of the measures for the first category is to fuse LiDAR data with other kinds of RS data. Jensen et al. (2008) utilized ALS data in conjunction with SPOT5-derived spectral vegetation indices (SVIs) in order to figure out the extent to which integration of ALS and spectral data can estimate specific LAI over a broad range of conifer forest stands. Zhao and Popescu (2009) used ALS-based LAI derivations to validate satellite LAI products. Recently, more synthetic canopy models were built in order to retrieve more accurate LAI quantities (Richardson et al., 2009) and LAI-associated structure parameters, such as angular canopy closure and vertical canopy cover (Korhonen et al., 2011). The brief strategy for the measures of the second category is to assume airborne LiDAR with sampling densities as high as possible, along with the quick development of LiDAR quality within these recent ten years.

However, almost all of the previous ALS-based studies (Lefsky et al., 1999; Lovell et al., 2003; Lim et al., 2003; Riano et al., 2004; Houldcroft et al., 2005; Morsdorf et al., 2006; Jensen et al., 2008; Zhao and Popescu, 2009; Richardson et al., 2009; Korhonen et al., 2011; Hopkinson et al., 2013) were deployed at the plot or even stand scale, and this trend continues in the latest studies on ALS-based LAI retrievals (e.g. Sabol et al., 2014; Tang et al., 2014). Among these latest studies, LAIs were derived based on the proposed feature parameters such as LiDAR penetration index (LPI) (Sabol et al., 2014) or LiDAR-characterized canopy gap probability (CGP) (Tang et al., 2014), instead of directly considering the vertical distributions of laser points within each crown. The lacking of the attempts of applying ALS for real-sense tree-level LAI retrievals is evidenced by the brief literature review conducted by Alonzo et al. (2015). In the context of airborne LiDAR featured with sampling densities increasing as the technology improves, can this situation be changed? Specifically, are current ALS systems avail-

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