Agricultural and Forest Meteorology 262 (2018) 279–297

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Seasonal change of leaf and woody area profiles in a midlatitude deciduous forest canopy from classified dual-wavelength terrestrial lidar point clouds

Zhan Li[a,*], Alan Strahler[b], Crystal Schaaf[a], David Jupp[c], Michael Schaefer[d,e], Pontus Olofsson[b]

[a] School for the Environment, University of Massachusetts Boston, 100 Morrissey Blvd., Boston, MA, 02125, USA
[b] Department of Earth and Environment, Boston University, 675 Commonwealth Ave., Boston, MA, 02215, USA
[c] CSIRO Land and Water, GPO Box 1700, Canberra, ACT, 2601, Australia
[d] CSIRO Agriculture and Food, GPO Box 1700, Canberra, ACT, 2601, Australia
[e] Australian Plant Phenomics Facility, The High Resolution Plant Phenomics Centre, CSIRO Agriculture and Food, GPO Box 1700, Canberra, ACT, 2601, Australia

ARTICLE INFO

Keywords:
Lidar
Dual-wavelength
3-D classification
Accuracy assessment
LAI
Vertical profile

ABSTRACT

This study demonstrates the retrieval of separate vertical height profiles of leaf and woody areas in both leaf-off and leaf-on seasons at a largely broadleaf deciduous forest site in the Harvard Forest of central Massachusetts, USA, using point clouds acquired by a terrestrial laser scanner (TLS), the Dual-Wavelength Echidna® Lidar (DWEL). Drawing on dual-wavelength information from the DWEL, we classified points as leafy or woody hits using their near-infrared (1064 nm) and shortwave infrared (1548 nm) apparent reflectance coupled with the 3-D spatial distribution patterns of points. We developed a new indirect assessment approach that quantified the accuracies (user's, producer's and overall) and variance of accuracies of the 3-D point classifications. The overall classification accuracy estimated by this indirect approach was 0.60 ± 0.01 – 0.77 ± 0.01 for leaf-off points and 0.71 ± 0.02 – 0.78 ± 0.01 for leaf-on points. These estimated accuracies were then utilized to adjust the proportions of separate gap probabilities to reduce the biases in the separate leaf and woody area profiles due to classification errors. Separate retrievals of leaf and woody area profiles revealed the change in their spatial heterogeneity over the 1-ha plot with season. These retrievals also allowed height-explicit estimation of the woody-to-total ratio, which is an empirical parameter often used to remove woody contributions to leaf area index retrievals made by optical methods. The estimates suggested the woody-to-total ratios generally stayed stable along height in the middle and upper canopy for this site but varied in the lower canopy. More accurate estimates of leaf area and its vertical profile are important for better measurement and modeling of the radiation regime of forest canopies, and thus their photosynthetic capacity. By separating leafy and woody materials in three dimensions, dual-wavelength TLS offers the prospect of better understanding of forest cycling of matter and energy within local and global ecosystems.

1. Introduction

Forest canopy structure regulates radiation interception through the canopy, affects the canopy microclimate, and consequently influences the energy, water, and carbon fluxes between soil, vegetation and atmosphere through interactions with leaf photosynthesis (Baldocchi et al., 2002). Leaf area index (LAI), defined as half of the total leaf surface area (simply referred as 'leaf area') per unit ground area (Chen and Black, 1992), governs the radiation interception through forest canopy and the capacity of canopy photosynthesis, and thus is one of the primary canopy structural measures used in both ecophysiological models and remote-sensing based estimation of net primary productivity (NPP) (Baldocchi et al., 2002; Bonan, 1993; Hanson et al., 2004; Medvigy et al., 2009; Running and Coughlan, 1988). In addition to LAI, detailed ecophysiological modeling of NPP requires realistic representations of the 2-D and 3-D distribution of leaf areas, e.g. vertical foliage profile, especially for open canopies and multi-layered forest stands (Law et al., 2001). Measurements of vertical foliage profile have been shown to be closely related to forest functioning measures (Parker et al., 2004; Stark et al., 2012), demonstrating the important role of accurate 3-D distributions of leaf area.

LAI and vertical foliage profiles are typically measured across different spatial scales. Almost all the methods to estimate LAI and vertical foliage profiles over large areas require ground truth data to calibrate and validate the empirical and physical retrieval models. Thus, the quality and detail of the ground truth data are quite important. The

* Corresponding author.
E-mail address: zhanli1986@gmail.com (Z. Li).

https://doi.org/10.1016/j.agrformet.2018.07.014
Received 17 February 2018; Received in revised form 10 July 2018; Accepted 13 July 2018

major methodologies for ground-based LAI measurements generally fall into two categories: (1) direct, which involves destructive sampling or litter-fall collection, and (2) indirect, which involves tree allometry, or gap probability measurements (Asner et al., 2003; Bréda, 2003; Chen et al., 1997; Jonckheere et al., 2004). The indirect, noncontact optical methods based on gap probability theory have been evaluated and adopted extensively across numerous field campaigns and studies due to their low cost, consistency and practicality of data collection (Bréda, 2003; Chen et al., 1997; Jonckheere et al., 2004; Jupp et al., 2009; Zhao et al., 2012). Ground-based measurements of vertical foliage profiles date back to early work, including stratified clipping and inversion of leaf contact frequency measured by point quadrats or by a camera with telephoto lens (Aber, 1979; MacArthur and Horn, 1969). Vertical foliage profile has also been obtained by taking LAI measurements using hemispherical photography acquired from a crane over increasing canopy height (Weiss, 2000). All these early methods are time-consuming, inconvenient, and often impractical. Recent ground-based active optical methods with terrestrial laser scanners (TLS) have demonstrated great potential to expeditiously measure gap probabilities at different canopy heights from lidar returns associated with ranges in 3-D space, and thus the accurate retrieval of vertical foliage profiles (Béland et al., 2011; Calders et al., 2014a; Jupp et al., 2009; Zhao et al., 2011).

However, the gap probability measurements used by all of these optical methods to measure LAI or vertical foliage profile typically include both leaves and woody materials, and thus actually measure plant area index (PAI, of both leaves and woody materials) and its vertical profile. The contribution of woody material to LAI measurements is usually removed with an empirical estimate of the woody-to-total ratio. Kucharik et al. (1998) found the nonrandom positioning of branches/stems with regard to leaves can cause inaccurate LAI values with the use of this simple ratio correction, especially when branches/stems are not preferentially shaded by leaves. Therefore, they proceeded to remove the woody contribution in the PAI directly using a Multiband Vegetation Imager. But this approach cannot remove the woody contribution at different canopy heights to correct vertical foliage profiles. Thus, a measure of the separation of leaves from woody materials in 3-D space is needed to remove the woody contribution in vertical foliage profiles.

Moreover, the separation between leaves and woody materials in 3-D can also improve the simulation and inversion of ecophysiological and 3-D radiative transfer models. Kobayashi et al. (2012) found the effect of woody elements on energy balance simulations in ecophysiological modeling is not negligible for heterogeneous landscapes due to the radiation absorption and heat storage by the woody elements. Some studies have also shown that the explicit inclusion of woody elements in 3-D radiative transfer models improves the canopy reflectance modeling (Widlowski et al., 2014) and thus model inversions to estimate both biophysical (Malenovský et al., 2008) and biochemical variables (Verrelst et al., 2010) at high resolution.

Furthermore, measures of the 3-D separation between leaf and woody materials is also required by recent advances in fine-scale architectural tree modeling and aboveground biomass (AGB) estimation methodology. Recent studies (Bremer et al., 2017, 2018) reconstructed near-realistic architectural tree models of deciduous forest sites from TLS data but the approach used requires the skeletonization of leaf-off scans for branch and twig modelling. The separation of leaf and woody materials will help such architectural modeling of mixed or evergreen forests when leaf-off scans are not possible. Recent TLS-based nondestructive approaches to AGB estimation combine *a priori* wood density information with wood volumes that have been directly calculated from cylinder tree models built from TLS point clouds using Quantitative Structure Modeling (QSM) (Burt et al., 2013; Calders et al., 2014b; Kaasalainen et al., 2014; Raumonen et al., 2013). This nondestructive approach is independent of allometric equations, and has been validated against destructive sampling of a eucalyptus forest, showing overestimation errors of ~10% by QSM as compared to an underestimation error of ~30%–37% using allometric equations (Calders et al., 2014b). Previous QSM trials on both simulated and real TLS point clouds have suggested that lidar returns from leaves are an important error source in modeling trunk and branch structures for wood volume estimates (Burt et al., 2013), leading to the conclusion that the removal of leaf points from 3-D lidar point clouds should improve the accuracy of woody structure modeling.

Three-dimensional scans of forests by TLS have shown the potential of separating leaves from woody materials in 3-D space. However, currently only a few studies have been focused on the classification of leaves and woody materials in 3-D space. Some earlier studies explored coarse discrimination of leaves from trunks or from both trunks and big branches via the manual manipulation of lidar scans (Hosoi and Omasa, 2007; Watt and Donoghue, 2005). Automatic 3-D classification of lidar point clouds has been attempted to separate leaves and woody materials by thresholding the lidar return intensities from TLS operating with shortwave infrared (SWIR) bands (1550 nm or similar) (Béland et al., 2014; Olsoy et al., 2014) or with a green band (532 nm) (Clawges et al., 2007), though the selection of intensity thresholds is rather subjective and needs adjustment from scan to scan. Yang et al. (2013) used lidar return pulse shapes from a full-waveform TLS for classification of leaf and branch lidar hits. However, the compound effects of reflectance, size, and orientation of targets may generate similar return intensities or return pulse shapes from different target classes (Li et al., 2016; Yang et al., 2013). Ma et al. (2016) attempted to improve the point classification by developing a geometric-based automatic forest point classification algorithm using spatial distribution patterns of points for preliminary separation and a series of post-processing filters of various threshold parameterizations to achieve final classifications. Zhu et al. (2018) found that the 3-D point classification was improved by using both radiometric and geometric features of points at varying spatial scales.

With a growing number of 3-D point classification approaches being developed, appropriate accuracy assessments of these classifications are needed to compare and assess the different methods and inform consequent impacts on the estimation of leaf and woody areas and on vertical profiles. Achieving these objectives needs more than just visual inspections of classified point clouds but instead requires classification accuracy estimates from rigorous quantitative assessments. While quantitative assessment of 2-D image classifications has been practiced by numerous studies and recently thoroughly summarized by Olofsson et al. (2013, 2014), few studies have addressed appropriate quantitative accuracy assessment for these newly emerged 3-D point classification methods. One of the most challenging problems for assessing 3-D point classifications is to find an independent reference classification of higher quality than the 3-D classified point cloud to be evaluated. Such 3-D reference classification datasets are extremely rare or lacking, particularly for forest scans. Therefore most current studies of 3-D point classifications to date have simply presented visual inspections as a demonstration of their classification quality (Béland et al., 2014; Clawges et al., 2007; Hosoi and Omasa, 2007; Watt and Donoghue, 2005). Some studies have further addressed the assessment of 3-D classifications via the destructive sampling of leaf and woody biomass (Olsoy et al., 2014), which is not only quite difficult and costly but also only provides a proxy of the overall accuracy. A recent study by Ma et al. (2016) reported quantitative accuracy assessment including the values of overall, user's and producer's accuracies (ranging from ~60% to 95% without estimating variance) that have been commonly used in 2-D image classification assessments. Zhu et al. (2018) also reported the overall accuracies (84.4% without estimating variance) of point classifications and carried out an indirect assessment by comparing the leaf-wood ratios of a whole canopy from 3-D point classifications and digital hemispherical photo classifications. The reference dataset for these accuracy assessment of point classifications came from the visual inspection of points in lidar scans aided by information from hemispherical photos. However, depending on laser beam divergence and