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Reliability and limitations of a novel terrestrial laser scanner for daily monitoring of forest canopy dynamics

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ABSTRACT

Leaf area index (LAI) or plant area index (PAI) are commonly used to represent canopy structure and dynamics, but daily estimation of these variables using traditional ground-based methods is impractical and prone to multiple errors during data acquisition and processing. Existing terrestrial laser scanners can provide accurate representation of forest canopy structure, but the sensors are expensive, data processing is complex, and measurements are typically confined to a single event, which severely limits their utility in the interpretation of canopy trends indicated by remotely sensed data. We tested a novel, low-cost terrestrial laser scanner for its capacity to provide reliable and successive assessments of canopy PAI in an evergreen eucalypt forest. Daily scans comprised of 920 range measurements were made by three scanners at one forest site over a two-year period, providing mostly consecutive estimates of PAI, and of vertical structure profiles (as Plant Area Volume Density, PAVD). Data filtering, involving objective statistical methods to identify outliers, indicated that scan quality was adversely affected by moist weather and moderate wind speeds (>4 m s^{-1}), suggesting limited utility in some forest environments. Data cleaning (associated with sensor malfunctions) plus filtering removed 32 to 49% of scans, leaving on average 57% of data over the two-year period. Nonetheless, we found strong agreement between lidar-derived PAI estimates, and those from monthly hemispherical images (±0.1 PAI); with both methods indicating mostly stable PAI over multiple seasons. The PAVD profiles from the laser scanner indicated that leaf flush in the upper canopy concomitantly balanced leaf loss from the middle canopy in summer, which was consistent with measured summer peaks in litter fall. This clearly illustrated the advantages of three-dimensional lidar data over traditional two-dimensional PAI estimates in monitoring tree phenology, and in interpreting changes in canopy reflectance as detected by air- and space-borne remotely sensed data.

1. Introduction

Describing canopy structure is essential for many ecosystem studies since it strongly affects net primary productivity, and regulates the sub-canopy light, temperature and moisture environment. Forest growth is strongly linked to canopy dynamics because the canopy structure determines how much photosynthetically active radiation is intercepted and hence how much of that energy can be utilized for growth (Landsberg & Sands, 2011).

Leaf area index (LAI, defined as the single-sided leaf area per unit ground area) is the variable most commonly used to represent canopy structure and dynamics in ecosystem models (Gower & Norman, 1991; Leuning, Cleugh, Zegelin, & Hughes, 2005; Soegaard, 1999). The LAI of forests varies with species composition, forest developmental stage, prevailing site conditions, seasonality, management practices, and broader climate/biogeography (Ellis & Hatton, 2008; Jonckheere et al., 2004). LAI can change rapidly with seasons, particularly in deciduous forests, and can also be affected by discrete events like windstorms, drought and fire (Weiss, Baret, Smith, Jonckheere, & Coppin, 2004). Hence, a high temporal resolution of LAI dynamics has been noted as critical for accurate estimation of key forest-level processes including CO_2 flux, evapotranspiration, water and light interception, and decomposition (Breda, 2003; Chason, Baldocchi, & Huston, 1991).

Terrestrial and airborne lidar data have the potential to describe the canopy structure and can provide accurate estimates of LAI (Dassot, Constant, & Fournier, 2011; Zhao et al., 2013). Lidar data have traditionally been acquired as onetime events, creating a snapshot in time, which severely limits their utility in the interpretation of canopy trends without facing considerable labour and acquisition costs. A recent study by Calders et al., 2015 used a Riegl terrestrial lidar for multiple campaigns to monitor deciduous forest structure over a period from leaf off to leaf on (150 days), but such studies are not feasible for ongoing monitoring due to the expense of traditional laser scanners and the requirement for manual operation. Satellite-based observations of LAI (e.g. MODIS)

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provide more frequent spatially averaged data, but observations don't differentiate between the over- and understorey in more complex ecosystems. This can cause large fluctuations of LAI and discrepancies between satellite-based estimates when compared with ground-based methods (Ryu et al., 2012).

A range of ground-based direct and indirect methods offer scope to accurately estimate LAI and to validate remote sensing products (e.g. MODIS, LANDSAT, airborne lidar and radar). Direct methods like whole-tree harvesting or litter collection are the most accurate but are labour intensive, time consuming and destructive, and thus only marginally feasible for regular sampling over large areas (Jonckheere et al., 2004; Moser, Hertel, & Leuschner, 2007). Indirect ground-based measures of LAI are based on light transmission through the canopy and are often faster and automated, allowing for a larger spatial sample compared to direct measurements (Jonckheere et al., 2004). They involve measurements of gap fraction and gap size distribution, which depend on leaf angle, leaf form, and leaf clumping. Hemispherical images provide the most widely used photographical method for ground-based indirect measures of LAI (Chianucci & Cutini, 2013). They are fast to sample in the field, and usually correlate well with other optical-based methods (such as the LAI-2000; Fang, Li, Wei, & Jiang, 2014; Jonckheere et al., 2004; Thimonier, Sedivy, & Schleppi, 2010). Nonetheless, they are still labour intensive (non-automated, restricted to particular light conditions), and are prone to measurement bias caused by prevailing light conditions and exposure settings while sampling. They also depend on threshold settings during image processing, which are generally subjective and themselves dependent on the incident light distribution (Beckschaefer, Seidel, Kleinn, & Xu, 2013; Macfarlane, Hoffman, et al., 2007; Zhang, Chen, & Miller, 2005).

Eucalypt forests represent challenges to both direct and indirect measures of LAI due to their long leaf life-spans (three or more years; Pook, 1984), vertical leaf orientation, deviation from a spherical leaf distribution and clumping of foliage (Macfarlane, Arndt, et al., 2007). Many eucalypts are known to grow opportunistically, without clear seasonal pattern, and to react quickly to climatic stress through, for example, foliage shedding in summer (Pook, 1984). Detection of such unpredictable and potentially rapid changes in LAI requires canopy observations of consistently high temporal and spatial resolution, which is commonly lacking in most of the traditional ground-based LAI methods. In addition, these methods provide a two-dimensional assessment of crown dynamics, providing little scope to assess leaf dynamics at different heights in an evergreen crown.

Evergreen forests present particular challenges for detecting changes in LAI. Without the complete leaf loss of deciduous forests, it is rarely possible to accurately estimate the relative contributions of woody and leafy components to LAI estimates, or to separate the overstorey from the understorey to validate satellite-based LAI estimates. Since standard techniques for acquiring LAI in evergreen forests do not distinguish between light intercepted by the foliage and that intercepted by non-foliage parts of the tree, LAI can be more accurately described as a plant area index (PAI; Chason et al., 1991; Hutchison et al., 1986; Thimonier et al., 2010).

This study examined the utility of a new terrestrial light detection and ranging (lidar) scanner 'VEGNET' (Culvenor, Newnham, Mellor, Sims, & Haywood, 2014) for detecting seasonal canopy dynamics in evergreen forests. VEGNET is a simplified laser scanner that makes ~920 range measurements during a full azimuth scan at a fixed zenith angle of 57.5°, and records the distance to each scatterer observed. This laser scanner offers many advantages over traditional methods, including: i) consecutive and automated monitoring of canopy dynamics on a daily basis (offering unprecedented temporal resolution); ii) night-time scans (removing interpretation errors associated with subjective image exposure and threshold settings); iii) and provision of a three-dimensional perspective of crown dynamics as a vertical profile of Plant Area Volume Density (PAVD, Culvenor et al., 2014). It is more affordable than full hemispherically scanning terrestrial laser scanners, but lacks the point density and spatial detail provided by such instruments (e.g. Echidna Validation Instrument or Riegl; Dassot et al., 2011; Strahler et al., 2008). Two recent studies have indicated the capability of the VEGNET scanner to detect leaf fall in a deciduous forest (Portillo-Quintero, Sanchez-Azofeifa, & Culvenor, 2014), and to provide repeated measures of PAI and PAVD in a eucalypt forest (Culvenor et al., 2014). However, we are still lacking an assessment of how VEGNET operates over longer time periods, how its repetitive measurements of PAI compare to other methods, and an objective method for data filtering and quality control. The main aim of this study was therefore to test the reliability of this novel laser scanner in a temperate eucalypt forest, by i) examining the potential for objective and generic methods for data filtering; ii) characterising the level of agreement of lidar-derived PAI estimates with those from other methods over multiple seasons; and iii) evaluating capacity to capture vertical crown dynamics over multiple seasons.

2. Materials and methods

2.1. Study site description

The study site was located around the 'Wombat Flux' eddy-covariance flux tower in the Wombat State Forest in central Victoria, south-eastern Australia (37° 25′ 19.988″ S, 144° 05′ 39.998″ E, elevation 705 m asl). The forest is a dry sclerophyll 'Open Forest' (Specht, 1981), widespread in south-eastern Australia. The dominant eucalypt species are: *Eucalyptus obliqua* (messmate stringybark), *Eucalyptus rubida* (candlebark), and *Eucalyptus radiata* (narrow-leaved peppermint). The average canopy height is ~22 m (tree heights typically range from 15 to 30 m with a few isolated taller specimens). The understory is sparse, mainly consisting of a discontinuous ground-layer of native perennial grasses and Austral bracken (*Pteridium esculentum*). The climate is Mediterranean to cool temperate, with long-term average rainfall of 871 mm, and a mean annual temperature of 12.1 °C (2001–2012). Temperatures range from a mean monthly minimum of 3.4 °C in July to a mean monthly maximum of 25.6 °C in January; winters are generally cold and wet, while summers are warm and dry (Hinko-Najera, Fest, Livesley, & Arndt, 2015). Prior to the study, the site had been selectively harvested up to the 1970s, and was periodically burnt by low-intensity prescribed fire; this management history is typical of similar mixed species eucalypt forests of south-eastern Australia.

2.2. Instrument description

The VEGNET scanner (CSIRO, Australia) is a simplified and low-cost version of existing terrestrial laser scanners like Riegl VZ-400 (Calders et al., 2015), FARO Photon 120 (Pueschel, Newnham, & Hill, 2014), Leica C10 (Hancock et al., 2014) or Echidna (Zhao et al., 2013), and was designed for automated daily monitoring of crown structural dynamics rather than extracting detailed measures of forest structure at any one point in time. The sensor head consists of an inclined 45° prism that fixes the scan angle to 57.5° zenith (hinge angle, Jupp et al., 2009). The prism rotates through 360° azimuth during a complete scan. The class 2 red laser (635 nm, 0.6 mrad beam divergence) has an effective range of 60 m for green foliage, making it suitable for monitoring the structure of forests with canopy heights up to approximately 30 m. Distance to canopy objects is measured using phase-based range-finding, whereby range is inferred from the phase shift between transmitted and reflected laser energy modulated at a known frequency (Culvenor et al., 2014; Pueschel et al., 2014). The chance of multiple hits is minimised by the very low beam divergence, but partial and multiple hits can be visually observed in the canopy. Night-time operation is required due to the wavelength of the range finder to produce reliable range estimates of up to 60 m. The slow sample rate of the range finder (2–0.25 Hz) does not allow visually distinguishing the exact target, but the largest uncertainty with range recordings is assumed to be in the