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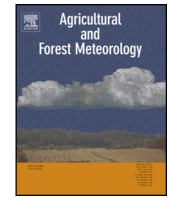

Comparison of optical LAI measurements under diffuse and clear skies after correcting for scattered radiation

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ABSTRACT

Leaf area index (LAI) is a forest canopy variable that is closely related to forest growth and health. The LAI-2000 Plant Canopy Analyzer is widely used for indirect measurement of LAI; however, use of the instrument is limited to diffuse sky conditions, greatly restricting sampling. A new bidirectional transmission model allows measurements to be obtained under clear sky conditions. This is accomplished by calculating a correction factor to reduce the impact of scattered light from canopy elements on gap fraction estimates. In this study we evaluate this technique by contrasting LAI measurements taken under diffuse and clear skies in a *Pinus radiata* D. Don plantation. We also evaluate the importance of obtaining accurate needle optical properties to parameterise the scattering correction model. Clear sky LAI estimates calculated with (a) measured optical values of *P. radiata* needles, (b) default values from the instrument software, and (c) maximum published values were compared to diffuse sky LAI estimates. Agreement was strongest where measured optical properties were used ($R^2 = 0.87$), with the relationship weakening under the default ($R^2 = 0.78$), and maximum value ($R^2 = 0.67$) scenarios. Under these three scenarios average clear sky LAI exceeded diffuse sky LAI by 16%, 17%, and 22%, respectively. The disagreement was due in part to erroneous measurements from the outer sensor ring under diffuse skies. With these data removed agreement improved markedly under all scenarios ($R^2 = 0.94$, 0.89, and 0.75, respectively), and the mean differences under each scenario declined to 8%, 9%, and 15%, respectively. Measurement of LAI under clear skies appeared to reduce error in the outer ring, greatly reduced logistical constraints, and reduced errors associated with sky variability.

1. Introduction

Leaf area index (LAI) is defined as one half the total leaf surface area per unit ground area (Jonckheere et al., 2004). In forest ecosystems LAI is a key variable in a range of processes including: gas and energy exchange, water and nutrient cycling, canopy health and primary production (Bréda, 2003). For forest managers, LAI is valuable for use in hybrid growth models (Mason et al., 2012) and as a tool for assessing the impact of management practices such as fertilisation (Carlyle, 1998; Peduzzi et al., 2012).

Despite its fundamental importance to forest managers and scientists, LAI usage has been limited by the difficulty of obtaining rapid and accurate measurements. In deciduous forests litter traps can provide accurate estimates of LAI, but in evergreen forests direct measurement relies on destructive sampling of representative trees (Chen et al., 1997). Although this approach provides accurate measurements of LAI, the process is labour intensive and costly (Beets et al., 2011; Küßner and Mosandl, 2000; Mason et al., 2012).

A variety of methods have been developed that allow indirect measurement of effective LAI (*Le*), which includes all light blocking elements (hereafter referred to as LAI), to be assessed using optical instrumentation. Hemispherical canopy photography (HCP) and the LAI-2000 (LI-COR Biosciences Inc., Lincoln, NE, USA) are two of the most widely used methods, and the accuracy of both has benefited from ongoing improvements in theory and technique (Macfarlane et al., 2014; Ryu et al., 2010; Woodgate et al., 2015). Despite these improvements, both instruments suffer from limitations that make measurement of LAI challenging in forest canopies. In the case of HCP, accurate estimation of LAI requires correct classification of canopy and sky elements in order to calculate the gap fraction. This constrains image acquisition to diffuse sky conditions where the contrast between sky and foliage is greatest, and requires careful attention to image exposure and post processing (Macfarlane et al., 2014; Zhang et al., 2005).

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The LAI-2000, and the newer LAI-2200, have been widely used to obtain indirect measurements of LAI for several decades (e.g. Chen et al., 2006; Stenberg et al., 1994; Welles and Cohen, 1996). The instrument measures sky brightness in the blue band (320–490 nm) using five concentric light sensor rings centred at zenith angles of: 7°, 22°, 38°, 52°, and 68°. Canopy transmittance can be calculated by comparing measurements taken above and below a plant canopy, and it is then possible to estimate gap fraction, LAI, mean foliage orientation, and apparent canopy clumping (LI-COR, 2015). Estimation of these variables relies on the assumption that multiple scattering of solar radiation by canopy elements is minimal in the blue band. Measurements taken under clear skies can seriously violate this assumption, and scattered light reaching the below canopy sensor can cause LAI to be underestimated by up to 26% (Kobayashi et al., 2013; Leblanc and Chen, 2001). To minimise the impact of scattered light, LAI measurement is restricted to diffuse sky conditions. However, the impact of scattered light is not completely eliminated, and measurements under diffuse conditions have been observed to underestimate LAI by up to 8% due to scattering (Kobayashi et al., 2013). Finally, in tall canopies suitable sampling conditions are often further constrained by the need to acquire above canopy readings in clearings some distance away from below canopy measurements (Solberg et al., 2009). Under these circumstances differences in sky brightness will be confounded with canopy transmission. Therefore, a large expanse of uniformly diffuse sky is required to minimise potential error in LAI introduced by variations in sky brightness between locations (LI-COR, 2015).

A new bidirectional transmission model proposed by Kobayashi et al. (2013) quantifies the impact of scattered light on gap fraction estimates obtained from the LAI-2200. The Kobayashi et al. (2013) model (hereafter the Kobayashi model) has been implemented as a software-based scattering correction model for LAI-2200 data, and is included with the latest iteration of the instrument—the LAI-2200C. The basic principle of operation remains the same with some additional features and protocols that are briefly outlined here. Given solar zenith, azimuth, and prevailing sky conditions the Kobayashi model predicts the impact of scattered light on gap fraction measurements obtained across the view zenith range of the LAI-2200C sensor located below a simplified one-dimensional canopy. To implement the model, a GPS receiver in the LAI-2200C records accurate time and position data to reconstruct solar position at the time of measurement.

The Kobayashi model requires parameterisation with measurements of diffuse sky radiance, fraction of diffuse light in the blue band, and leaf optical properties. The sky variables can be measured using the LAI-2200C (Kobayashi et al., 2013; LI-COR, 2015). However, obtaining leaf optical properties is more challenging. Although Kobayashi et al. (2013) demonstrate a method for obtaining these values in broadleaf species using the LAI-2200C, the technique is cumbersome when applied to needle leaf species. This method requires obstruction of a small view hole close to the size of a single needle, followed by arrangement of needles to cover a large diffuse panel. These species also pose a challenge when measured with a spectroradiometer, and published values can vary depending on the protocol employed (Yanez-Rausell et al., 2014). As such, the accuracy of the LAI-2200C method for needle leaved species is unclear. Where accurate measurements are available from published results, reflectance measurements may not cover the blue band used by the LAI-2200, and data for transmittance are often absent.

The scattering correction model promises to greatly expand the range of conditions under which LAI can be measured using the LAI-2200C, removing a major obstacle to measurement of LAI at larger scales. However, the expanded range of sampling conditions raises questions about the comparability of diffuse measurements and scatter corrected clear sky measurements. In-situ validation of the Kobayashi model was limited to a well characterised oak-grass savanna woodland, and revealed differences between diffuse and scatter corrected clear sky LAI (Kobayashi et al., 2013). Comparisons of in-situ measurements obtained from coniferous forests are lacking at present.

In this study we aim to evaluate the agreement between LAI measurements obtained using the LAI-2200C under clear and diffuse sky conditions. This was accomplished using repeated measurements from 21 plots located in an intensively managed *Pinus radiata* D. Don forest under ideal sky conditions. We also examined the effectiveness of the scattering correction model in improving data collected from the error prone outer ring. This is of interest as the outermost ring observes the largest portion of the hemisphere, but valuable canopy information is often lost due to scattered light or gap fraction saturation (Gower et al., 1999; Kobayashi et al., 2013; Leblanc and Chen, 2001). Finally, we present needle spectra obtained from *P. radiata* needles using a new method for measuring small leaved species with a spectroradiometer (Noda et al., 2013). These data were combined with default optical properties suggested by the LAI-2200C software, and published values measured using older protocols to form three needle optical property scenarios. The impact of each scenario on the calculated scattering corrections and the agreement between clear and diffuse sky LAI was examined.

2. Materials and methods

2.1. The forest plots

Data were acquired from Kaingaroa forest which is located in the Central North Island of New Zealand (38.67S; 176.46E). Kaingaroa is New Zealand's largest contiguous plantation covering around 180,000 ha. The majority of the forest occupies the pumice plateau within the Central North Island and has generally flat topography. Sample plots were restricted to stands of *P. radiata* which cover 92% of the total forested area. Individual stands are typically homogenous in terms of age, silvicultural treatment, and stand density.

2.2. Plot selection and layout

Permanent sample plots (PSPs) are maintained throughout Kaingaroa forest, and a subset of these plots were chosen for the study. PSP locations were determined using a systematic sampling approach where the nodes of a grid with random origin and orientation form plot centres. Within the forest, the plot centre for each 600 m^2 circular plot was located using a Trimble Geo6000 XH GNSS (Trimble Navigation Ltd., Sunnyvale, CA, USA).

In tall forest canopies, the size and location of clearings available for a reference sensor to collect open sky readings can constrain measurement protocol and accuracy (see Section 2.3). To address this, we used satellite imagery to identify clearings within the forest that satisfied the following criteria: (1) unobstructed view of the sky across a wide azimuth, (2) at least 200 m × 200 m in size, (3) vegetation less than 3.5 m tall.

PSPs adjacent to suitable clearings were selected for measurement. In total, 21 plots covering a wide range of stand densities (200–917 stems ha^{-1}) were selected (Table 1). Estimates of stand height ranged from 17 m to 39 m (mean of 18 m), while stand ages ranged from 10 to 26 (mean and median of 18). The LAI measurements were conducted in early spring (September–October, 2014), with the time between diffuse and clear sky measurements of any plot minimised to avoid seasonal fluctuations in LAI. With the exception of plot 18, all plots were on relatively flat terrain, and the average straight-line distance to a clearing was 1.1 km.