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Estimation of leaf area index in eucalypt forest using digital photography

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Abstract

We tested whether leaf area index (L) in eucalypt vegetation could be accurately estimated from gap fraction measurements made using both fisheye and non-fisheye digital photography. We compared methods that measure the gap fraction at a single zenith angle (0° or 57°), with fisheye photography that measures the gap fraction at multiple zenith angles. We applied these methods in an unthinned stand of the broadleaf tree species *Eucalyptus marginata* that had an initial L of 3. We removed one-third of the trees and reapplied the methods, and then removed another one-third of the trees and applied the methods a third time. L from the photographic methods was compared to L obtained from destructive sampling and allometry. We found that L was accurately estimated from non-fisheye images taken at the zenith, providing that the total gap fraction was divided into large, between-crown gaps and smaller, within-crown gaps, prior to using the Beer–Lambert law to estimate L. This rapid and simple method corrected for foliage clumping and provided estimates of crown porosity, crown cover, foliage cover and the foliage clumping index at the zenith, but required an assumption about the light extinction coefficient at the zenith. Fisheye photography also provided good estimates of L but only if the images were corrected for the gamma function of the digital camera, and the combined Chen–Cihlar and Lang–Xiang method of correcting for foliage clumping was used. The clumping index derived from fisheye images was insensitive to thinning but the calculated foliage projection coefficient was. Methods of obtaining and analysing gap fraction and gap size distributions from fisheye photography need further improvement to separate the effects of foliage clumping and leaf angle distribution.

Keywords: Eucalypt forest; Leaf area index; Digital photography; Gap fraction; Canopy cover; Clumping index

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1. Introduction

Eucalypts are increasingly important worldwide—both to industry and to local and regional carbon and water budgets (see, for example, Hubbard et al., 2004), and there is an obvious need to obtain accurate estimates of their leaf area index (L). L is an essential input into many models of eucalypt growth and water use (Linder, 1985; Comins and McMurtrie, 1993; Beadle et al., 1995; Landsberg and Hingston, 1996; Hingston et al., 1998; Snow et al., 1999; Croton and Barry, 2001) as well as being an essential component of comparative studies of many leaf-level attributes such as transpiration and water use efficiency (e.g. Hubbard et al., 2004). Estimates of L are difficult to obtain in forest owing to the labour required to destructively sample many trees, and to recognised problems with indirect methods of estimating L. This has prompted the development of visual guides for estimating L (e.g. Sampson et al., 1997; e.g. Cherry et al., 2002) and, mainly within Australia, the development and use of the "Adelaide method" (Andrew et al., 1979), which is based on counting the number of similar clumps of foliage in the canopy. These visual methods require a limited amount of destructive sampling for calibration (O'Grady et al., 1999) and can still be time consuming.

The Licor LAI-2000 plant canopy analyser (PCA, Licor Inc., Lincoln, Nebraska) has gained wide acceptance for estimating L but the cost of this instrument can be prohibitive. Furthermore, the PCA is known to underestimate L by 10–40% (Macfarlane et al., 2000), partly because of scattering of blue light (Chen, 1996). Hemispherical or fisheye photography is a cheaper alternative to the PCA and has been applied successfully in stands of *Eucalyptus globulus* (Macfarlane et al., 2000). Both fisheye photography and the PCA measure the gap fraction at multiple viewing angles in order to analytically separate and quantify both foliage area and foliage angle. Technical and theoretical obstacles have until recently prevented wide spread adoption of fisheye photography. Fisheye photography required metering exposure, adjusting lens settings, film development, negative scanning, conversion of colour images to black and white, and image analysis with specialised software. The accurate reproduction of pixel brightness theoretically requires control using an optical density wedge throughout the process (Wagner, 1998), but this has rarely been undertaken. Other sources of error in fisheye photography include photographic exposure and choice of threshold. Darker images give larger L and automatic exposure metered beneath the canopy can result in inaccurate estimates of L (Macfarlane et al., 2000; Zhang et al., 2005).

Digital photography eliminates several steps from fisheye photography and attempts have been made to resolve other issues. Correct exposure can be determined beneath tall canopies with a handheld 'spot' light meter (Olsson et al., 1982; Clearwater et al., 1999; Walter et al., 2003). To some extent varying the threshold can correct for incorrect exposure, but thresholding is often subjective and can introduce errors as well as remove them. Wagner (2001) and Wagner and Hagemeier (2006) demonstrated that, when exposure is inconsistent, the two-value threshold method provides better estimates of L and of the leaf angle distribution than analysis of binary thresholded images (images converted from greyscale to black-and-white based on a single threshold). Leblanc (2004) recently released DHP (Digital Hemispherical Photography), the first freely available software product that incorporates a two-value threshold method.

Notwithstanding these improvements in image capture and analysis, the interpretation of results from fisheye photography can be problematic. Most indirect methods estimate the effective plant area index (L_t) rather than actual L as a result of the contribution of woody elements to the total plant cover, which results in overestimation of L, and clumping of foliage, which results in underestimation of L. Generally, corrections for woody area are between 5 and 30% (Gower et al., 1999) while corrections for clumping may be larger (Fassnacht et al., 1994; Kucharik et al., 1997). The clumping index, $\Omega(\theta)$, is the ratio of effective plant or leaf area index to the actual plant or leaf area index. $\Omega(\theta)$ equals 1 when foliage is randomly distributed in a canopy but is less than 1 as foliage becomes more clumped. L_t, $\Omega(\theta)$ and the foliage projection coefficient, $G(\theta)$, together determine the canopy gap fraction, $P(\theta)$ according to the modified Beer–Lambert law (Eq. (1) based on Nilson, 1971) where θ is the zenith angle. Hence, to accurately estimate L from gap fraction distributions it is necessary to also know $\Omega(\theta)$ and the ratio of woody area to total plant area.

$$P(\theta) = \exp\left(-\frac{G(\theta)\Omega(\theta)L_t}{\cos(\theta)}\right) \qquad (1)$$

Most of the clumping in broadleaf canopies is at the tree level; large, non-random gaps exist between broadleaf trees while the foliage within crowns tends to be more randomly distributed (Kucharik et al., 1997). Clumping indices can be calculated from an analysis of the gap size distribution (Chen and Cihlar, 1995) in addition to