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Influence of woody tissue and leaf clumping on vertically resolved leaf area index and angular gap probability estimates

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ABSTRACT

Leaf area index *L* is a key vegetation parameter that can be used in soil–vegetation–atmosphere exchange modeling. To represent the structure of ecosystems in vertically distributed modeling, vertically resolved *L* distributions as well as vertical and angular gap probability P_{gap} distributions are needed, but they are rarely available. On the experimental side, studies often neglect woody plant components when using indirect methods for *L* or P_{gap} observations. This can lead to significantly biased results, particularly in semi-arid savannah-type ecosystems with low *L* values.

The objective of this study is to compare three non-destructive leaf area index measurement techniques in a sparse savannah-type cork oak canopy in central Portugal in order to derive vertically resolved *L* as well as vertically and angularly resolved P_{gap}. We used the established LAI-2000 device as well as fast digital cover photography (DCP), which was vertically and angularly distributed. We applied object-based image analysis to DCP to exclude woody plant components. We compared the results with vertically distributed LAI-2000 measurements and with vertical estimates based on easily measurable crown parameters.

Height and angularly distributed DCP was successfully applied here for the first time. It delivers gap probability P_{gap} and effective leaf area index L_e measurements that are comparable to the established LAI-2000. The height and angularly dependent leaf clumping index Ω could be determined with DCP, which led to a 30% higher total leaf area index *L* for DCP compared to LAI-2000. The exclusion of woody tissue from DCP yields on average a 6.9% lower leaf area index *L*. Including Ω and excluding woody tissue, the *L* of DCP matched precisely with direct measurements using litter traps. However, the set-up and site-specific adjustment of the image analysis algorithm remains challenging. We propose a special filter for LAI-2000 to enhance data quality when used in open canopies. Finally, if height-dependent observations are not feasible, ground-based observations of crown parameters can be used to derive very reasonable *L* height distributions from a single, ground-based *L* observation.

1. Introduction

Leaf area index *L* is defined as the one-sided leaf area per unit of ground area (Watson, 1947). It is an important structural parameter of plants, canopies and ecosystems and strongly influences amounts of carbon uptake (e.g. Bunce, 1989) and transpiration (e.g. Monteith, 1965), radiative energy absorbed and reflected by the canopy (Monteith, 1959) and the maximum capacity of rainfall interception (Rutter et al., 1971). The structural parameter quantifying the probability of a direct beam of radiation passing through the canopy without being intercepted by the foliage is the gap probability P_{gap} (Monsi and Saeki, 1953, 2005), which depends on *L*, tree density and other stand attributes. It controls the energy distribution between plant surfaces and the soil surface as well as within the plant (Chen and Black, 1992; Nilson, 1971) and, thus, the ecosystem albedo.

Multiple techniques exist and have been widely used to measure *L* and P_{gap}. Direct techniques include destructive sampling or litter traps (Jonckheere et al., 2004) and are not suitable for measuring P_{gap}. In general, they deliver the most precise results but are very labor intensive, and multiple observations during the year are often not feasible. Indirect techniques include the inclined point quadrat method (Warren Wilson, 1960, 1965), the

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Nomenclature

A	total number of pixels in each image (pxl)	εL	relative bias of leaf are index (%)
$f(\alpha)$	leaf angle distribution function (–)	L_e	effective leaf are index (m^2_{leaf}/m^2_{ground})
ff	foliage cover (–)	$\sum L_e$	cumulative effective leaf are index (m^2_{leaf}/m^2_{ground})
fc	crown cover (–)	$P_{gap}(\theta)$	gap probability (–)
$G(\theta)$	leaf projection function (–)	$\varepsilon P_{gap}(\theta)$	relative bias of gap probability (%)
gl	number of pixels in gaps between crowns (pxl)	r_c	crown radius (m)
gt	number of pixels in all gaps (gaps between crowns + gaps within crowns envelopes) (pxl)	$S_e(h)$	ellipsoidal crown shape model (–)
		$S_{e\,9/10}(h)$	asymmetric ellipsoidal crown shape model (–)
h	height above ground (m)	$S_t(h)$	triangular crown model (–)
h_t	height of the crown top (m)	θ	view zenith angle (°)
h_b	height of the crown bottom (m)	α	angle of the leaf's normal to the zenith (°)
$K(\theta)$	contact frequency (–)	θ_v	view angle span (°)
L	leaf are index (m^2_{leaf}/m^2_{ground})	W	wood area index (m^2_{wood}/m^2_{ground})
$\sum L$	cumulative leaf are index (m^2_{leaf}/m^2_{ground})	$\Omega(\theta)$	clumping index (–)

commercially available LAI-2000 plant canopy analyzer (LI-COR, 1992; Cutini et al., 1998), digital hemispherical (DHP) and digital cover photography (DCP) (Ryu et al., 2010b; Macfarlane et al., 2007a) and ground based lidar (Zhao et al., 2011; Danson et al., 2014). They deliver P_{gap}, L and other structural parameters of the canopy, such as crown cover and porosity (Macfarlane et al., 2007b). Most indirect techniques are based on the observation of P_{gap} and use the gap probability theory by Nilson (1971) to infer L. When commercial devices like the LAI-2000 are applied by inexperienced users, usually more attention is paid to the estimated L than to a proper quality control of the actual P_{gap} observations. This can lead to an undetected bias in L. A clear advantage of the LAI-2000 (LI-COR, 1992; Miller, 1967) as well as of DCP applied at $\approx 57.3^\circ$ (Macfarlane et al., 2007b; Pisek et al., 2011; Wit, 1965) is that they circumvent the need for information about leaf inclination angles α (Warren Wilson, 1960). However, for the angularly distributed application of DCP, knowledge about leaf inclination angles α need to be derived from observations. The impact of the used probability function for calculating leaf projection $G(\theta)$ from α is still under discussion (Wang et al., 2007). Further, DCP offers the advantage of using off-the-shelf digital cameras and providing a minimum of image distortion compared to DHP. Thus, common image analysis software can be used. Using methods based on P_{gap}, the influence of the spatially non-homogeneous distribution of leaves on P_{gap}, expressed as clumping index Ω, needs to be considered because the gap probability theory assumes random distributed light intercepting elements (Fassnacht et al., 1994; Nilson, 1971). This greatly influences L derivation in open, heterogeneous stands such as savannah-type ecosystems. However, estimating the spatial and angular distribution of Ω within a plant stand remains challenging (Leblanc et al., 2005; Ryu et al., 2010b).

Because recent model development in soil–vegetation–atmosphere transfer modeling (De Pury and Farquhar, 1997; Sellers et al., 1987; Sinclair et al., 1976) or radiative transfer schemes (Jacquemoud et al., 2000; Haverd et al., 2012) aims for high-resolution multi-layer models (Baldocchi, 1997), the demand for vertically resolved P_{gap} and L is increasing. Although vertically distributed observations in tree canopies are challenging (Meir et al., 2000), expensive and often not feasible, several observation approaches have been applied (Beadle et al., 1982; Hutchison et al., 1986; Parker et al., 1989; Strachan and McCaughey, 1996; Wang et al., 1992). Such approaches either required labor-intensive destructive sampling, heavy equipment, and 'above canopy readings' with a tower, or were not able to incorporate Ω. Recent studies have proven that ground-based lidar offers high performance estimating vertical L profiles including leaf clumping (Zhao et al., 2011; Danson et al., 2014), but require special software and available instruments are still very cost intensive.

The contribution of woody tissue (e.g., stems, branches, twigs) to observed gap probability P_{gap}, and thus inferred leaf area index L, is still an unsolved problem for indirect measurements. It is assumed to introduce substantial biases depending on the ecosystem type L (Chen et al., 1997a,b; Deblonde et al., 1994; LI-COR, 1992). Commonly, observations during leafless periods are used to estimate wood area index W and subtract it from L, which is only feasible in deciduous forests (Deblonde et al., 1994; Ryu et al., 2012) and assumes a random distribution of woody tissue with respect to the position of the leaves. Only a few approaches attempt to quantify this influence (Kucharik et al., 1998) and to our knowledge, it has not yet been included directly in computations. In this treatment, an image analysis approach is developed directly excluding woody tissue from P_{gap} calculations enabling a direct quantification of the bias for the first time.

The aim of the present study is to compare the performance of the established LAI-2000 against the DCP method with respect to leaf clumping effects, methodological biases and the influence of woody tissue. We derive height and angularly dependent gap probability P_{gap} and height dependent leaf area index L in an open savannah-type woodland. Additionally, we test a ground-based approach to estimate height dependent L when height distributed measurements are not feasible. We address the following research questions: (1) How do gap probability P_{gap}, leaf area index L and clumping index Ω change with height and view zenith angle? (2) How strong is the influence of non-homogeneity on both methods? (3) How does the image size of DCP influence the accuracy of gap probability P_{gap} and leaf area index L observations? (4) How strong is the influence of woody tissue on gap probability P_{gap} and leaf area index L? (5) How well can we derive height distributed leaf area index L with only ground-based observations?

2. Material and methods

2.1. Theory

2.1.1. Gap probability theory

Beer's law for the absorption of light by particles (Bouguer, 1729; Beer, 1852) is used to relate leaf area index L to the gap probability P_{gap} of the canopy (Nilson, 1971):

$$P_{gap}(\theta) = \exp\left(\frac{-G(\theta)L\Omega(\theta)}{\cos(\theta)}\right) \quad (1)$$

where $P_{gap}(\theta)$ is the gap probability of the canopy, $G(\theta)$ is the leaf projection function, L (m^2_{leaf}/m^2_{ground}) is the leaf area index