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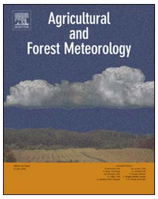

Estimating structural parameters of agricultural crops from ground-based multi-angular digital images with a fractional model of sun and shade components

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ABSTRACT

Accurate and efficient in situ measurement methods of leaf area index (LAI) and leaf angle distribution (LAD) are needed to estimate the fluxes of water and energy in agricultural settings. However, available methods: to estimate these two parameters, especially LAD, are limited. In this study, we propose a field measurement method using multi-angular digital images to estimate LAI and LAD simultaneously from the area proportions of: (i) sunlit soil; (ii) sunlit leaves; (iii) shaded soil; and (iv) shaded leaves. A new expression of the fraction of sunlit leaves is developed based on the radiative transfer theory. Coupling the measured and modeled fractions with an optimization scheme, LAI and the LAD parameters are derived from inverting a fractional model of sunlit and shaded leaves and soil. Through four tests using simulated scenes and in situ measurements for row crops, it is determined that our method performs well. The absolute error of LAI estimation is less than 0.1 when LAI is low (i.e., < 1.2), and the absolute deviations of LAI estimates are approximately 0.5 when the reference LAI is 3.5. The estimation errors of LAI and the G function (a representative of LAD which quantifies the projection of unit foliage area) for in situ measurements are respectively less than 0.2 and 0.06 in general. In addition, the accuracy of estimation is even higher when leaves are simulated as randomly distributed disks or observations from multiple azimuth planes are used. One of the most interesting features of this method is its ability to estimate reasonable LAD directly from the fractions of sunlit and shaded leaves, even when LAI is high (i.e., > 3), so little background soil is seen. The sensitivity and uncertainty analysis is consistent with the estimation errors. Theoretically, the application of this method is not limited to row crops or to field measurement, as the derived formulae of sunlit and shaded components can be used for other types of vegetation by introducing the clumping index and can be used in the modeling of canopy vegetation parameters (e.g., canopy reflectance).

1. Introduction

Leaf area index (LAI) and leaf angle distribution (LAD) are critical vegetation parameters for a wide range of biophysical models and applications. LAI accounts for the one-side leaf area per unit ground surface area and is used as an essential input in (often coupled) climate, ecosystem, hydrology, and carbon cycle models (Jonckheere et al., 2004; Myneni et al., 1989; Ross, 1981; Running and Coughlan, 1988). LAD describes the geometric status of leaves, determining the radiant environment of a plant, and thus plays a crucial role determining the intra- and inter-canopy energy and mass balances and micro-meteorology (Hikosaka and Hirose, 1997; Pisek et al., 2011; Thanisawanyangkura et al., 1997; Wang et al., 2007). LAI is a basic parameter that is typically obtained through large field observational

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Nomenclature

symbols

H	Canopy depth (m)
z	Depth of a specific location in a plant canopy (m)
sL	Leaf dimension (m)
d_L	Leaf diameter (m)
r_L	Unit vector of the leaf normal
r_s	Unit vector directed to the sun
r_v	Unit vector directed to the observer
θ_s	Solar zenith angle (in radians)
θ_v	View zenith angle (in radians)
φ_s	Solar azimuth angle (in radians)
φ_v	View azimuth angle (in radians)
μ_i	Cosine of intersection angle between r_i and the normal of horizon
$u_L(z)$	Foliage area density (m^{-1})
Ω	Clumping index
θ_L	Inclination angle of leaf normal (in radians)
Φ_L	Azimuth angle of leaf normal (in radians)
$g_L^*(\theta_L)$	Probability density function of LAD under the assumption of uniform distribution of the leaf azimuth angle
$B(u, \nu)$	Beta function
u	a parameter in beta function related to leaf angle distribution
v	a parameter in beta function related to leaf angle distribution
$G(r_i)$	Mean projection of the unit foliage area in direction r_i
$P_g(z, r_s, r_v)$	Bidirectional gap fraction at depth z in a plant canopy
$P_g(r_s, r_v)$	Fraction of sunlit soil
$P_c^t(r_s, r_v)$	Total fraction of sunlit leaves
$P_c(r_s, r_v)$	Fraction of sunlit leaves, considering the brightness variation due to the angle between the solar rays and the leaf normal
$P_z(r_s, r_v)$	Fraction of shaded soil
$P_t(r_s, r_v)$	Fraction of shaded leaves
$P_v(r_v)$	Fraction of leaves
p_L	Normalized leaf brightness, indicating the probability of a leaf to be classified as "sunlit leaves"
$\Gamma(r_s, r_v)$	Normalized area scattering phase function
R_L	Leaf reflectance
T_L	Leaf transmittance
k	Ratio of leaf transmittance to leaf reflectance
$P(\theta)$	Gap fraction at the zenith angle θ
$\hat{P}_g(z, r_s, r_v)$	Bidirectional gap fraction at depth z in the row canopy
$\hat{P}_g(r_s, r_v)$	Fraction of sunlit soil in the row canopy
$\hat{P}_c(r_s, r_v)$	Fraction of sunlit leaves in the row canopy
$\hat{P}_v(r_v)$	Fraction of leaves in the row canopy
l_i	Relative path length of illumination or view direction
a_i	Ratio of $G(r_i)$ to μ_i
$\hat{a}_i$	Product of $G(r_i)$ and l_i
D	Leaf area density for row crops (m^{-1})
w_r	Width of vegetated hedgerow (m)
w_s	Width of soil (m)
$P_{c/v}$	Ratio of the fraction of sunlit leaves (P_c) to the total fraction of leaves (P_v)
$F(x)$	Frequency of vegetated pixels those possess the brightness of x
Y	Cost function in the inversion process
N	Number of observations in the inversion process
$f_{i,j}(X)$	Model-predicted value with a vector variable X as input
$P_{i,j}$	Observed bidirectional fraction
LAI	Leaf area index
LAD	Leaf angle distribution
LAI_e	Effective LAI
RGB	Red-Green-Blue
PP	Principal plane
PPP	Plane perpendicular to principal plane
PR	Row-perpendicular plane
R	Row-parallel plane
ALL	All planes of PP, PPP, PR and R
ROI	Region of interest
FOV	Field of view

experiments. However, only a few field campaigns have measured LAD (Li, 1994; Buermann and Helmlinger, 2005 Buermann and Helmlinger, 2005). Rapid, stable, and reliable field measurement methods for both LAI and LAD remain necessary.

Methods that quantify LAI from field measurements can be classified into two categories: direct and indirect (Breda, 2003; Jonckheere et al., 2004). Although indirect LAI measurements methods have been widely used for decades (Neumann et al., 1989; Chen, 1996; Zou et al., 2009; Campbell et al., 1999; Buermann and Helmlinger, 2005; Baret et al., 2005), they suffer: (i) when foliage distribution is heterogeneous and (ii) due to the lack of a measured LAD. Discrepancies have been found between the homogeneous assumption of Beer's Law and its application in vegetated land-surfaces with high heterogeneity (Hu and Yan, 2012). To address the heterogeneity, various algorithms have been proposed, including the finite-length averaging method (LX; Lang and Xiang, 1986), the gap-size distribution method (CC; Chen and Cihlar, 1995; Leblanc, 2002; Miller and Norman, 1971a), a combination of the finite-length and gap-size distribution methods (CLX; Leblanc et al., 2005), the path length distribution method (PATH; Hu et al., 2014), etc. Compared to LAI, LAD is more difficult to measure because the effects of LAI and LAD on canopy reflectance are convolved; thus, pragmatic methods for measuring LAD are sparse. Recently a method was proposed and applied to estimate LAD from ground-based images acquired with a leveled digital camera (Pisek et al., 2011; Ryu et al., 2010; Zou et al., 2014; McNeil et al., 2016). However, an automatic method for indirect LAD measurement is still lacking. In addition, both LAI and LAD have impacts on gap fractions, making it challenging to resolve LAI and LAD with unidirectional gap fraction observations.

Bidirectional gap fraction contains more information than the traditional unidirectional gap fraction and provides the potential to simultaneously retrieve LAI and LAD. Bidirectional fractions directly relate to vegetation canopy structural parameters and have shown to be effective when estimating LAI (Andrieu et al., 1994; Casa and Jones, 2005; Zeng et al., 2015). When both sunlight and viewer geometries penetrate the canopy four basic fractions are formed, being: (i) sunlit soil; (ii) sunlit vegetation; (iii) shaded soil; and (iv) shaded vegetation (Fig. 1). The four fractions affect the signals of the first order of light scattering and contribute to LAI retrieval (Liao et al., 2013). Kuusk (1991) determined the fraction of sunlit soil to describe the hot-spot of radiative transfer in the vegetation canopy. The hot-spot effect in optical remote sensing is a phenomenon characterized by a reflectance peak in the direction of incident radiation (due to not viewing any shadow). Jupp and Strahler (1991) developed an expression of the hot-spot to construct an optical model that accounted for the bidirectional reflectance observed in a forest. The geometric optical model (Li and Strahler, 1985) expressed canopy reflectance using the four fractions. Specific expressions were proposed for the row-structure vegetation to model canopy radiation or reflectance (Chen et al., 2002; Yan et al., 2002; Ren et al., 2013; Yu et al., 2004). Casa and Jones (2005) proposed a method to estimate LAI and LAD by inverting a ray-tracing