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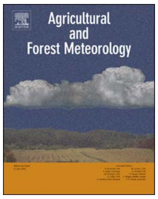

Research paper

A robust leaf area index algorithm accounting for the expected errors in gap fraction observations

Alemu Gonsamo[a,*], Jean-Michel Walter[b], Jing M. Chen[a], Petri Pellikka[c,d], Patrick Schleppi[e]

[a] Department of Geography and Planning, University of Toronto, Toronto, ON, Canada
[b] Institut de Botanique, Faculté des Sciences de la Vie, Université de Strasbourg, Strasbourg CEDEX, France
[c] School of Geography and Remote Sensing, Nanjing University of Information Science and Technology, Nanjing, China
[d] Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland
[e] Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland

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ABSTRACT

The leaf area index, LAI, representing the physiological and structural functions of vegetation canopies, can be estimated from gap fraction measurements obtained at different zenith angles. Earlier works have provided practical and convenient theoretical solution to retrieve LAI based on the integration of contact numbers (a projected area of leaves on a plane perpendicular to the view or solar zenith angle) over zenith angles as obtained by a linear regression, i.e., LAI = 2(*A* + *B*), where *A* and *B* are the coefficients of the regression of contact numbers against zenith angles. This graphical procedure is equivalent to the more accurate method of LAI retrieval by integrating gap fraction measurements from nadir through horizon angles. However, using an ordinary least-squares regression on inherently unsteady relationship between contact numbers and zenith angles limited the use of a simple graphical procedure for LAI estimation. In this study, we introduce the use of robust procedure to retrieve regression coefficients (i.e., *A* and *B*), and assess the performance of the new procedure using numerically derived hypothetical data, computer simulated and real measurements of hemispherical photographs. Our results indicated, the new procedure not only outperformed the ordinary least-squares solution for graphical procedure, but also outperformed all existing LAI methods We conclude from analyses using numerically derived hypothetical data, computer simulated and real measurements of hemispherical photographs that estimating *A* and *B* (where LAI = 2(*A* + *B*)) using a robust procedure is a convenient and sufficiently accurate method for estimating LAI from field measurements of gap fractions at different zenith angles.

1. Introduction

Leaf area index (LAI, one-half the total leaf surface area per unit of horizontal ground surface area (Chen and Black, 1992)) is an important physiological and structural property of vegetated landscapes. A wide range of models used in agriculture, ecology, carbon cycle, climate and other related studies use LAI to estimate radiation, heat, momentum, water, and various gas exchanges. For example, LAI is one of the essential climate variables defined by the Global Climate Observing System (GCOS) that are important in improving the parameterization of the land surface-atmosphere interaction processes in a range of models (GCOS, 2011).

LAI can indirectly be estimated *in situ* from the observations of gap fraction or the fraction of light transmission under forest canopies (Breda, 2003; Jonckheere et al., 2004; Weiss et al., 2004). The mathematical analyses for retrieving LAI from both gap fractions and contact numbers (i.e., the logarithm of gap fraction) are very similar and have been presented in cascades of methods in the second half of the 20th century (Wilson, 1959, 1963; Miller, 1964, 1967; Nilson, 1971; Campbell, 1986; Lang, 1986; Lang and Xiang, 1986; Lang, 1987; Chen and Cihlar, 1995; Norman and Campbell, 1989; Ross, 1981). Briefly, the probability of gap fraction (P_0) for a given LAI can be described by Poisson distribution:

$$P_0(\theta) = e^{-\mathrm{LAI}\frac{G(\theta)}{\cos\theta}} \tag{1}$$

where P_0 is a gap fraction (a probability of non-interception of incident light) for a direction defined by zenith angle θ, and G is the mean projection of a unit leaf area in the direction of θ and onto a plane normal to θ. From Eq. (1), the following expression can be derived:

$$-\cos\theta \ln P_0(\theta) = \mathrm{LAI}G(\theta) = K(\theta) \tag{2}$$

where $K(\theta)$ is the mean contact number. The mean contact number is

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[*] Corresponding author.
E-mail addresses: gonsamoa@geog.utoronto.ca, ggalex2002@yahoo.com (A. Gonsamo).

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Table 1
Summary of sampling and optical errors on gap fraction (P_0) data especially near zenith ($\theta = 0°$) and horizon ($\theta = 90°$) angles.

Source of error	Cause, statistical nature of error	Location of P_0 data
Large weight of single gaps	Sampling, random depending on clumping	Especially important near zenith
Too few gap samples	Sampling, random especially at high LAI	Near the horizon
Interference of trunks	Sampling, systematic depending on trees	Especially near the horizon
Objects beyond plot limits	Sampling, more or less systematic	Especially near the horizon
Topography	Sampling, more or less systematic	Especially near the horizon
Light scattering	Optical, random depending on sun elevation	Potentially all angles
Unsharpness (“mixed pixels”)	Optical, systematic depending on focus	Especially near the horizon
Motion blur (by wind)	Optical, random depending on speed	Especially near zenith
Lens vignetting	Optical, systematic depending on zenith angle	Near the horizon

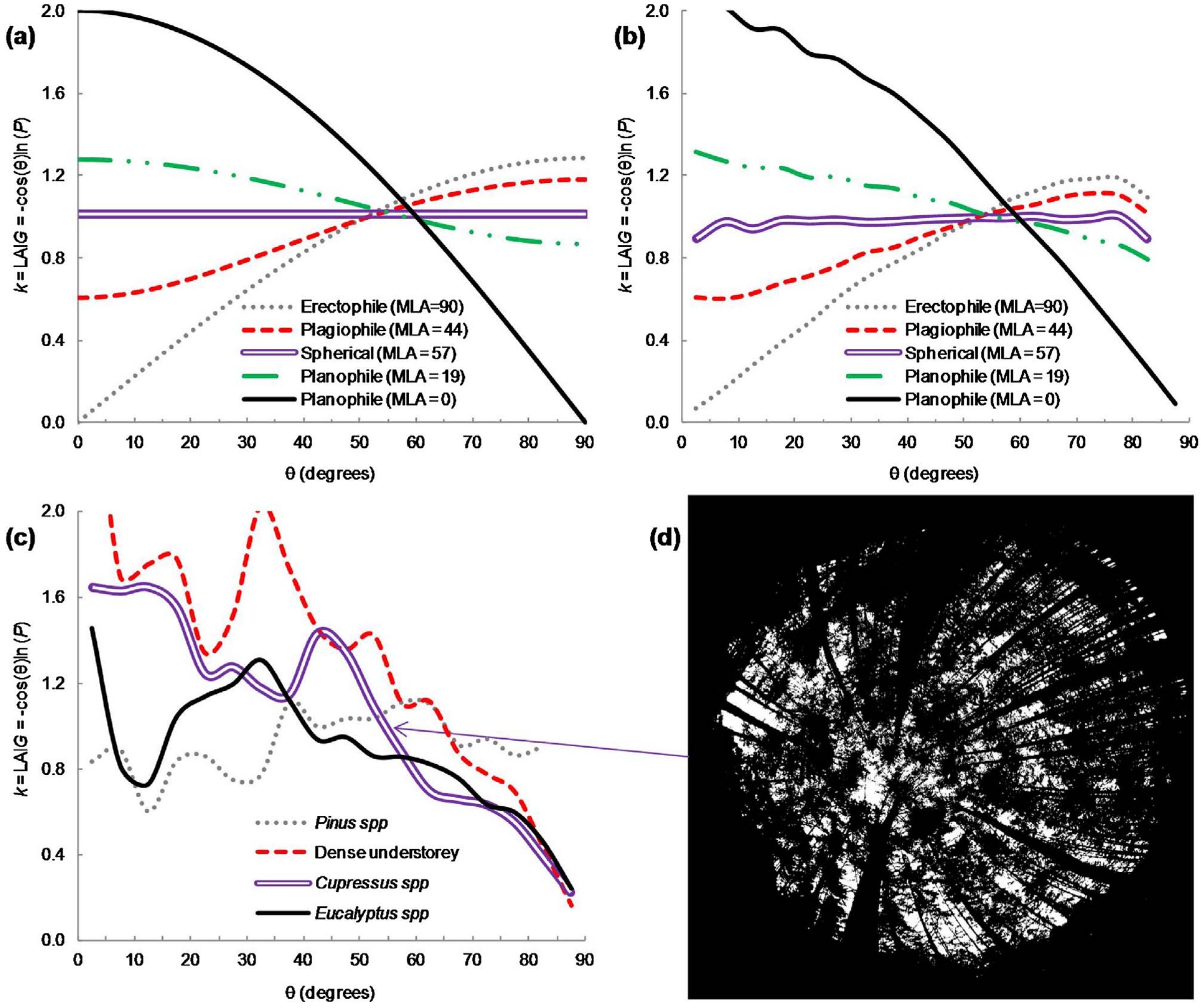

Fig. 1. Typical contact numbers, *K*, as functions of zenith angles (*θ*) and mean leaf angles (MLAs) of idealized canopies with leaf area index (LAI) value of 2 (a), *K* derived from computer simulated hemispherical photographs (Schleppi et al., 2007) for LAI value of 2 and various MLAs (b), *K* derived from true hemispherical photographs taken on various forest types (with various LAI therefore *K* does not converge at *θ* value of 57.3°) (c), and example hemispherical photograph plotted in (c) for *Cupressus* spp. Plantation, from Taita Hills, South-East Kenya (Gonsamo and Pellikka, 2008) (d). The five canopy MLAs considered in (a) and (b) are: erectophile (vertical leaves with MLA = 90°), plagiophile (predominantly inclined leaves with MLA = 44°), spherical (the relative frequency of leaf angle is the same as for surface elements of a sphere, with MLA = 57°) and two planophile (one with predominantly horizontal leaves with MLA = 19° and the other is horizontal leaves with MLA = 0°).

determined by the overlapping of projected areas of leaves on a plane perpendicular to the direction of the ray of light (i.e., θ), which penetrates the canopy along a given path length. Lang (1987) argued that $K(\theta)$ can be recovered from Eq. (2), using the relationship:

$$K(\theta) = A + B\theta \tag{3}$$

where A is the intercept and B is the slope of the regression of $K(\theta)$ (i.e., $-\cos\theta \ln P_0(\theta)$) against θ in radians. Using the original Miller’s integral (Miller, 1964, 1967) for flat leaves with symmetry about azimuth yields:

$$\mathrm{LAI} = 2 \int_{\theta=0}^{\theta=\pi/2} K(\theta) \sin\theta \, d\theta \tag{4}$$