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Comparison of methods for measuring gap size distribution and canopy nonrandomness at Järvselja RAMI (RAdiation transfer Model Intercomparison) test sites

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ABSTRACT

Methods for analyzing foliage nonrandomness by means of the TRAC instrument, digital hemispheric photography, and a gap fraction model are assessed at two RAMI (RAdiation transfer Model Intercomparison) mature stands in Järvselja, Estonia. The six different methods involve calculation of the canopy element clumping index, at scales coarser than that of a shoot. The major aim was to define the merits and limitations of the various methods. We conclude the gap size distribution and beyond-shoot clumping is very stable across the stands for the solar zenith angle range from 30° to 60°. Estimates based on the gap size distribution and the combination of gap size and logarithm methods performed the best while compared with an independent gap fraction model. We clarify the effect of the assumed leaf inclination angle distribution on gap size distribution and differences between estimates of beyond-shoot clumping. We show that the modified, gap-size distribution based method of Chen and Cihlar can provide reliable beyond-shoot clumping estimates without any a priori assumptions about the total gap fraction, segment length or the leaf inclination angle distribution. We also illustrate the changes in element clumping with measurement height. The compiled data extend the original parameter dataset to be used in the next phase of RAMI for different benchmark tests and reflectance modeling experiments, and contribute toward systematic validation efforts of radiative transfer models, operational algorithms, and field instruments, as promoted by the Committee on Earth Observation Satellites (CEOS).

1. Introduction

RAdiation transfer Model Intercomparison (RAMI) was designed as an ongoing mechanism to benchmark radiation transfer (RT) models used to simulate the transfer of radiation at or near the Earth's terrestrial surface, i.e. in plant canopies and over soil surfaces (Pinty et al., 2001). For the future phases of intercomparisons, one of the expected goals would be to investigate the potential of RT models to reproduce in situ measurements of transmitted light by various methods such as Tracing Radiation and Architecture of Canopies (TRAC; 3rd Wave Engineering, ON, Canada) instrument or digital hemispherical photography (DHP) (Widlowski et al., 2007). The intensive collection of the optical measurements in the RAMI-selected real world forest stands is thus required.

Besides the information about the canopy gap fraction (P) and radiation regime at the forest floor, concurrent TRAC and DHP measurements would be also vital to address current challenges of the indirect methods with respect to quantifying architecture of forest canopies. One of the recurrent themes for the investigations concerning the vegetation structure is clumping of plant canopies (Bréda, 2003; Walter et al., 2003). Clumping describes the spatial aggregation of foliage elements. The clumping has been quantified by the aggregation or dispersion parameter (Nilson, 1971; Lemeur and Blad, 1974), also called clumping index (Chen and Black, 1992). The clumping index (Ω) thus describes the level of foliage grouping within distinct canopy structures, such as tree crowns, shrubs, and row crops, relative to a random distribution (Nilson, 1971; Chen and Black, 1992; Weiss et al., 2004). Ω is useful in ecological and meteorological models because it provides additional structural information to the effective leaf area index L_e obtained from optical indirect measurements (Chen and Black, 1991), where L_e is defined as one half of the total area of light intercepting leaves per unit horizontal ground surface area, assuming the foliage spatial distribution is random (Black et al., 1991). Clumping, through a better separation of sunlit and shaded leaves, has profound effects on the radiation regime of a plant canopy and photosynthesis

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(Oker-Blom, 1985; Oker-Blom et al., 1983; Wang and Jarvis, 1993; Davi et al., 2006). Ω larger than unity implies the foliage is regularly distributed; $\Omega = 1$ for a random distribution and in the case of foliage more clumped than random, $\Omega < 1$ (Chen et al., 2005). Ignoring the clumping effects may lead to incorrect estimates of radiation interception and distribution within the canopy with important implications to modeling of fluxes (Lacaze et al., 2002; Walcroft et al., 2005).

As suggested by Chen (1996), the total clumping index Ω can be separated into two components (Ω_E/γ_E), which are measured separately in the field and in the lab. γ_E is the needle-to-shoot area ratio (Fassnacht et al., 1994; Stenberg et al., 1994; Chen et al., 1997) quantifying the effect of foliage clumping within a shoot (for reference values for different species see Bréda, 2003); for broadleaves $\gamma_E = 1$ (Chen et al., 1997). Element clumping index Ω_E includes the effect of foliage clumping at scales larger than the elements (shoots for needleleaf species and leaves for broadleaf species).

Various methods were proposed for the assessment of the nonrandom spatial distribution from field measurements (Lang and Xiang, 1986; Chen and Cihlar, 1995a,b; Kucharik et al., 1999; Nilson, 1999; Walter et al., 2003; Leblanc et al., 2005). Considerable differences were observed between the approaches to quantify Ω_E (e.g. Walter et al., 2003; Leblanc et al., 2005; Macfarlane et al., 2007; Gonsamo and Pellikka, 2009), yet the role of important factors, such as the common practice of assuming spherical leaf projection function, the choice of segment size (Chen and Black, 1992; van Gardingen et al., 1999), or the assumed consistency between measurements while using different instruments (Leblanc et al., 2005), has been seldom assessed (Kucharik et al., 1997; Ryu et al., 2010a; Gonsamo et al., 2010). This practice calls for a comprehensive investigation to evaluate the performance and consistency of the methods with the commonly used instruments, and to define their merits and limitations.

The objective of our study is to determine the canopy nonrandomness at one Silver birch and one Scots pine RAMI stand in Järvselja, Estonia. To achieve this goal, we acquired information about the leaf inclination angles θ_L, carried out extensive measurements by means of TRAC, DHP, and LAI-2000 instruments, and finally characterized Ω_E based on six different methods found in the literature. We report on the following issues: (a) how spatially homogeneous are the two Järvselja RAMI stands with respect to the foliage clumping; (b) how does Ω_E change with the view zenith angle (θ) and measurement height (h) over the stands; (c) what are the strengths and limits of various methods, and which one performs the best; (d) what are the implications of assuming spherical leaf distribution function on calculating Ω_E; (e) characteristics and goodness of the agreement between results derived from TRAC and DHP. Finally, we suggest a modification to an existing gap size distribution-based method of Chen and Cihlar (1995a) to provide reliable estimates of beyond-shoot clumping that requires no a priori assumptions common to the other tested methods.

2. Theory

2.1. Leaf projection function and leaf inclination distribution function

The leaf projection function (G) is the projection coefficient of unit foliage area on a plane perpendicular to the view direction (Ross, 1981). G is essential to calculate the canopy gap fraction P and light regime at specific view zenith angles (Ross, 1981). G may be expressed as (Warren Wilson, 1960, 1967):

$$G(\theta) = \int_0^{\pi/2} A(\theta, \theta_L) f(\theta, \theta_L) d\theta_L \quad (1)$$

$$A(\theta, \theta_L) = \begin{cases} \cos\theta \cos\theta_L, & |\cot\theta \cot\theta_L| > 1 \\ \cos\theta \cos\theta_L [1 + (2/\pi)(\tan\psi - \psi), & \text{otherwise} \end{cases} \quad (2)$$

where θ is view zenith angle, θ_L is leaf inclination angle, and $\psi = \cos^{-1}(\cot\theta \cot\theta_L)$. Several special distributions have been developed to describe leaf inclination distribution function $f(\theta_L)$ (for their overview see Weiss et al., 2004); Wang et al. (2007) evaluated the two-parameter Beta-distribution (Goel and Strebel, 1984) as the most appropriate for describing the probability density of θ_L:

$$f(t) = \frac{1}{B(\mu, \nu)} (1-t)^{\mu-1} t^{\nu-1} \quad (3)$$

where t is $2\theta_L/\pi$. The Beta function $B(\mu,\nu)$ is defined as:

$$B(\mu, \nu) = \int_0^1 (1-x)^{\mu-1} x^{\nu-1} dx = \frac{\Gamma(\mu)\Gamma(\nu)}{\Gamma(\mu+\nu)} \quad (4)$$

The leaf inclination distribution can be described by the gamma function and two parameters, μ and ν:

$$\mu = (1-\bar{t}) \left(\frac{\sigma_0^2}{\sigma_t^2} - 1 \right) \quad (5)$$

$$\nu = \bar{t} \left(\frac{\sigma_0^2}{\sigma_t^2} - 1 \right) \quad (6)$$

where σ_0^2 is the maximum standard deviation with expected mean t and σ_t^2 is variance of t (Wang et al., 2007).

2.2. Element clumping index

2.2.1. Clumping index from gap size distribution (Ω_{CC}, Ω_{CMN})

Ω_{CC} is given based on the gap size distribution from the corrected (CC) method of Chen and Cihlar (1995a) by Leblanc (2002):

$$\Omega_{CC}(\theta) = \frac{\ln[F_m(0,\theta)]}{\ln[F_{mr}(0,\theta)]} \frac{[1 - F_{mr}(0,\theta)]}{[1 - F_m(0,\theta)]} \quad (7)$$

where $F_m(0, \theta)$ is the accumulated canopy gap fraction, and $F_{mr}(0, \theta)$ is the reduced gap–size accumulated fraction after removal of the large, non-random gaps. $F_{mr}(0, \theta)$ is obtained by a sequential removal of large non-random gaps from the measured gap size accumulation curve $F_m(\lambda)$, until the pattern of gap size accumulation resembles that of an equivalent canopy with a random spatial distribution of foliage, $F_r(\lambda)$. $F_r(\lambda)$ is calculated following the modifications by Chen and Cihlar (1995a) to the original equation by Miller and Norman (1971) as:

$$F_r(\lambda) = \left(1 + L_p \frac{\lambda}{W_p}\right) \exp\left[-L_p \left(1 + \frac{\lambda}{W_p}\right)\right] \quad (8)$$

where

$$L_p = \frac{G(\theta) L}{\cos\theta} \quad (9)$$

and

$$W_p = \frac{W_E}{\cos\theta_p} \quad (10)$$

W_E is the width of an element projected on a plane perpendicular to the direction of the solar beam, λ is the size of gaps, and $\cos\theta_p$ is obtained following Chen and Cihlar (1995a). $\cos\theta_p$ compensates for the elongation of the element shadow on a horizontal plane in the direction of the transect (Chen and Cihlar, 1995b). While W_E can be found from the measurements of leaf or shoot samples, L (true leaf area index) is usually unknown because it is in fact the goal of finding appropriate Ω (Chen and Cihlar, 1995b). Chen and