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Modeling forest canopies with a hierarchical multi-ring Boolean model for estimating a leaf area index

Denis Allard [a,*], Raul López-Lozano [b,c], Frédéric Baret [c]

[a] Biostatistique et Processus Spatiaux (BioSP), INRA, Avignon, France

[b] European Commission, Joint Research Center, Institute for Environment and Sustainability, Ispra, Italy

[c] EMMAH, INRA, UMR 1114, Avignon, France

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ABSTRACT

The leaf area index (LAI), defined as half the total developed area of green photosynthetically active elements per unit horizontal ground area, is one of the key biophysical variables of vegetated surfaces. Optical devices developed to overcome the burden of time consuming, expensive and difficult to conduct sampling in tree canopies are based on the unrealistic assumption that leaves are uniformly distributed in the canopy. This assumption is violated when the leaf area density varies in the horizontal plane due to the clustering of leaves in trees. In this work, a hierarchical model in which leaves are represented as a second level Boolean model whose centers are distributed conditional on a first level Boolean model representing crowns is proposed. Crowns will be furthermore modeled as concentric rings with varying leaf density. Analytical expressions relating second order functions, such as variograms or covariance functions, to canopy structure characteristics such as LAI, leaf size, crown cover and crown radius will be established. From the fitting of these second order functions, the proposed Boolean model will be inverted to retrieve the LAI and canopy structure characteristics. The methodology is assessed over a number of simulated test cases including realistic 3D canopy structure of forest canopies.

* Corresponding author. Tel.: +33 432722171; fax: +33 432722182.
E-mail address: allard@avignon.inra.fr (D. Allard).

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1. Introduction

A leaf area index (LAI) is one of the key biophysical variables of vegetated surfaces, controlling energy and mass exchanges with the atmosphere. LAI is defined as half the total developed area of green photosynthetically active elements per unit horizontal ground area. Destructive methods are probably the most accurate ones for retrieving LAI in situ, but they are time consuming, expensive and difficult to conduct in tree canopies (forest and orchards). Specially designed optical devices have thus been developed to overcome these limitations through indirect methods based on light interception/light transmission (Bréda, 2003; Jonckheere et al., 2004; Weiss et al., 2004; Garrigues et al., 2008). One of the very common assumptions made is that leaves are uniformly distributed in the canopy, leading to the simple Poisson law (Nilson, 1971):

$$q_0 = e^{-k_e \mathrm{LAI}} \tag{1}$$

where q_0 is the gap fraction — proportion of the incoming light that reaches unobstructed to the soil surface — and k_e is the extinction coefficient, calculated from

$$k_e = \frac{G(\theta_s, \theta_l)}{\cos\theta_s}. \tag{2}$$

$G(\theta_s, \theta_l)$ is the projection function, i.e. the area of one unit of leaf area with inclination θ_l projected along the incoming light direction defined by its zenith angle θ_s. The assumption of a homogeneous distribution of leaf area is violated when the leaf area density (leaf area per unit canopy volume) varies in the horizontal plane. Under such conditions, methods based on the Poisson law result in systematic LAI underestimation (Lang and Xiang, 1986; Nilson, 1971). To extend the Poisson model to non-homogeneous canopies, Chen et al. (1997) and Kucharik et al. (1999) proposed to introduce the so called clumping parameter, Ω:

$$q_0 = e^{-k_e \Omega \mathrm{LAI}}. \tag{3}$$

The clumping parameter is lower than 1 when leaves are clustered and higher than 1 when leaves are regularly distributed, i.e. when they tend to fill preferentially gaps in the canopy. However, the clumping parameter is difficult to measure or estimate in situ and relies on prior assumptions on leaf size (Chen and Cilhar, 1995) or crown size (Nilson, 1999). Despite the existence of some measurement methods minimizing the effect of the clumping bias (Baret et al., 2010; Lang and Xiang, 1986; López-Lozano et al., 2007, 2009), retrieval of the actual LAI from the gap fraction measurements still remains a difficult problem because clumping may appear at several nested scales, from shoot, branch, tree/plant and stand.

This work focuses on the clumping at the stand scale, i.e. leaves grouped in vertically developed plants and for the vertical direction ($\theta_s = 0$) where the largest effects on gap fraction are expected. In the vertical direction, the extinction coefficient is simply the area of the projection of a unit leaf with inclination θ_l. We will exploit variograms and other second order functions describing the spatial correlation between gaps as observed from digital images. For this purpose, a more realistic model than the Poisson model described in Eq. (1) will be proposed. Based on the random sets theory and Boolean models (Matheron, 1975; Stoyan et al., 1995; Lantuéjoul, 2002) it introduces two original features to usual Boolean models. The first innovation is that we shall consider a hierarchical Boolean model: leaves will be represented by a second level Boolean model whose centers are distributed conditional on a first level Boolean model representing crowns. The second innovation is that crowns will be modeled as concentric rings.

The proposed model will combine these two features in a stationary context. Analytical expressions relating second order functions to canopy structure characteristics such as LAI, leaf size, crown cover and crown radius will be established. The proposed Boolean model will be inverted to retrieve canopy structure characteristics from the second order functions observed over a number of simulated test cases, including realistic 3D canopy structure of forest canopies. Section 2 presents the model and the theory, where full expressions of second order functions are derived. Section 3 presents how synthetic canopy images are built and Section 4 provides details on how the parameters of the hierarchical