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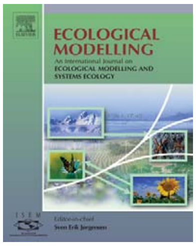

Could plant leaves be treated as Lambertian surfaces in dense crop canopies to estimate light absorption?

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ABSTRACT

Light absorption by plant organs affects the development of a canopy directly through photobiological processes as well as indirectly through its action on organ temperature. Recent radiative models enable light absorption to be estimated for each individual organ within a canopy. These models require parameters describing incident radiation, canopy structure, and optical properties of phytoelements. Among these parameters, the bidirectional optical properties of phytoelements are a stumbling block: they are difficult to measure and take into account efficiently. Thus, most radiative models resort to what is referred to the Lambertian approximation. However, few studies have verified its suitability. In this paper, we assess this approximation in terms of individual leaf absorption for dense crop canopies in the solar spectrum. Simulations were performed with Monte Carlo ray tracing for three canopies, three sun positions, and two spectral domains (photosynthetically active radiation (PAR) and near infrared (NIR)). Results validate the suitability of the Lambertian approximation to simulate the light absorption by plants given the conditions under study.

1. Introduction

Solar radiation regulates the growth and the development of plants because it is a source of energy for photosynthesis and energy budget and because its spectral composition acts as a signal for photomorphogenesis. For these phenomena, the radiative variable of interest is the amount of energy absorbed by phytoelements. Point monitoring of absorbed energy may be carried out experimentally by putting a large set of small sensors on leaves and stems within a canopy (Gutschick et al., 1985) or it may be estimated by using a radiative transfer model based on an explicit description of plant organs (Chelle and Andrieu, 1999). This study has inquired into the simulation approach.

A radiative model relies on three sets of variables and parameters, all required to define the angular distribution of radiance characterizing light coming from the sky, the canopy structure, and the optical properties of soil and phytoelements. The angular distribution of sky radiance can be measured or simulated (Perez et al., 1993; Zibordi and Voss, 1989). This distribution ranges from a nearly isotropic distribution in the case of overcast sky to a pseudo-Dirac distribution in the case of a clear sky. It plays a role in the penetration of incident light, but not in the light scattering from leaf to leaf.

The canopy structure is defined by the area, the shape, the position, the orientation, and the density of phytoelements within the canopy. This structure may be accurately described by representing each phytoelement with a set of geometric primitives. Different methods have been set up to do so: measuring by 3D digitizer (Drouet, 2003; Sinoquet and Rivet, 1997), using statistical distributions of parameters describing the shapes and positions of organs (España et al., 1999), or simulating plant growth (Prusinkiewicz, 1998).

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The canopy structure affects both the penetration of incident light and the multiple scattering between phytoelements.

The optical properties of phytoelements and soil result from their biochemical composition as well as from complex interactions between light and their structure. Two elementary processes occur: absorption and scattering. Absorption is quantitatively described by the spectral absorptance. Scattering is likewise described by the directional hemispherical reflectance (DHR) and directional hemispherical transmission (DHT), that is the fraction of the incident irradiance in a given direction that is reflected or transmitted by the surface (whatever the direction of reflection). DHR and DHT are usually measured with a spectral sensor mounted on an integrating sphere. As the integrating sphere is limited to a sole collimated light source, it measures DHR and DHT for a single direction of illumination and therefore does not provide the variation of DHR and DHT as a function of the direction of illumination, which may be non-negligible in the case of phytoelements e.g. the waxy maize leaf. Several models have therefore been developed to estimate DHR and DHT (Sinclair et al., 1973; Jacquemoud and Baret, 1990; Maier et al., 1999).

To describe canopy–light interactions, it is also necessary to know "how" the scattered light is angularly distributed. This is described by the bidirectional reflection distribution function (BRDF) and the bidirectional transmission distribution function (BTDF). The BRDF is the ratio between the radiance reflected or transmitted in a given direction i (corresponding to an infinitesimal solid angle) and the irradiance due to the light coming from a given direction r, that is "a concentration of reflectance per steradian" (Nicodemus et al., 1977). The BRDF is a function of five parameters: the wavelength (λ), the direction of incident light (i), and the direction of reflected light (r), where i and r are 3D vectors described by both a zenith and an azimuth angle. As a ratio of infinitesimals, a BRDF cannot be measured directly, as other derivative quantities such as speed (Nicodemus et al., 1977). Thus, while the concept of BRDF is useful for understanding and modeling light–surface interactions, measurements involving non-zero intervals of solid angle estimate bidirectional reflectance (more precisely biconical reflectance). An equivalent variable that is commonly measured is the bidirectional reflectance factor (BRF). It is the ratio between the radiance reflected by a surface and the radiance reflected by a perfectly diffuse surface under the same lighting conditions. The BRF is measured by sampling directions over a hemisphere with a spectrogoniometer (Brakke, 1994; Breece and Holmes, 1971; Jacquemoud et al., 2002; Sanz et al., 1997; Walter-Shea et al., 1989). Some models have been developed to estimate leaf bidirectional reflectance (Allen et al., 1973; Baranoski and Rokne, 2001; Bousquet et al., 2005; Govaerts et al., 1996; Kumar and Silva, 1973).

Accounting for actual leaf BRDFs within canopy radiative transfer (CRT) models has been primarily hampered by the lack of suitable data and parameterizations. Therefore, most CRT models resort to Lambertian scattering laws when dealing with the directional scattering properties of individual phytoelements. The Lambertian model handles BRDF or BDTF as a constant for any incident and scattering direction. This makes it attractive when describing light scattering by a single phytoelement in a CRT model. Herein below, this particular application of the Lambertian model is hereafter referred to the Lambertian approximation.

The Lambertian approximation is difficult to assess. Indeed, the multiple-scattered light within a canopy is a function of the spatial distribution of incident light, canopy structure, and scattering properties of phytoelements, and this function is strongly non-linear and spatially heterogeneous. The effect of leaf BRDF on canopy BRF for remote sensing applications has been studied e.g. by Ross and Marshak (1989); however, this effect has not been studied on the energy absorbed by individual leaves, a key variable for plant science. We investigated the validity of the Lambertian scattering approximation in the context of dense crop canopies. This was carried out by simulating light distribution for differing canopy structures and leaf BRDFs, using Monte Carlo ray tracing among the CRT models. The results of these simulations are presented in Section 3 for two contrasting spectral domains: the photosynthetically active radiation (PAR) (400–700 nm), highly absorbed by green leaves, and the near infrared (NIR) (700–1350 nm), little absorbed by green leaves. These two spectral domains are relevant to biological studies of photosynthesis and photomorphogenesis, respectively.

2. Simulation tools

2.1. *Monte Carlo ray tracing, a CRT model to test various leaf BRDF*

Accessing the light absorbed by individual leaves requires an explicit 3D description of the canopy structure as well as a radiative model taking into account this structural description. Such radiative models are known as surface-based radiative models (for an introduction, see Chelle and Andrieu (1999)). Among these models, we chose a Monte Carlo ray tracing model (MCRT) because it can handle both Lambertian and non-Lambertian leaf surfaces, the latter necessary to assess the Lambertian approximation. The MCRT model simulates the sequence of scattering and absorbing events incurred by a light ray, along its path from the sky to its extinction or its exit from the canopy (Ross and Marshak, 1988). The MCRT model has been widely used to simulate canopy BRF for remote sensing studies (see Disney et al. (2000) for a review). We have developed and tested such a model, now referred to as parcinopy (Chelle, 1997). It enables the simulation of infinite periodic canopies (Ross and Marshak, 1988) and the efficient sampling of scattering light directions from the leaf BRDF using importance sampling (Hammersley and Handscomb, 1964). It also enables the estimation of the surface density of absorbed energy (E_a) and associated variances for each leaf.

2.2. *Leaf BRDF models*

Measuring an entire phytoelement BRF and BTF is a real challenge because it is necessary to measure high gradients mainly in the specular peak as well as light scattered at grazing angles. An accurate sampling of incident and reflection directions in the hemisphere as well as spectral bands results in a large