MODELING PLANT LEAF BIDIRECTIONAL REFLECTANCE AND TRANSMITTANCE WITH A 3-D RAY TRACING APPROACH

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Abstract

A new radiative transfer model based on Monte Carlo ray tracing techniques of leaf optical properties has been developed, where the internal three-dimensional cellular structure is explicitly described to represent morphological properties of a typical dicotyledon leaf. The main objective of this work is to perform sensitivity analyses at different wavelengths to test the influence of the leaf internal structure as well as that of pigment and water concentrations on the light attenuation profile and the bidirectional scattering shape.

1 Introduction

Extracting quantitative information from remote sensing data requires analytical tools such as canopy reflectance models to interpret radiative measurements in terms of agronomical or ecological biophysical properties like leaf chlorophyll and water content, or canopy architecture [1]. In the optical spectral region, plant leaves may be considered basic scattering elements. It is therefore crucial to understand the mechanisms that govern the interactions of light with those elements and to model them both in terms of absorbed and scattered energy. Light attenuation inside leaves results from complex phenomena related to biochemical composition and anatomical features, while the epidermis determines the bidirectional reflectance. In the late sixties, the development of leaf radiative transfer models reflected the improved understanding of light interaction with plant leaves. Among the various approaches which have been suggested, only ray tracing techniques succeeded to account for the complexity of leaf internal structure as it appears from a microscope photography. This technique has been applied with a number of variants [2], [3], and [4]. The first two totally ignore absorption that characterizes the leaf optical properties outside the near-infrared (NIR) plateau. Moreover, leaves are always described as two-dimensional objects although the three-dimensional structure is very important to their function (*e.g.*, CO_2 or water diffusion) [5] and to light scattering. In this paper, we present a new three-dimensional light scattering model of a leaf where the internal structure is explicitly described to represent morphological properties of major species.

2 Leaf geometrical and optical properties

The geometrical description of the internal structure is based on a representation of a typical dicotyledon leaf containing an upper epidermis, palisade and spongy mesophylls, and a lower epidermis. The cells of each tissue are defined with geometrical primitives (spheres, ellipsoides, boxes, and cylinders) assembled with constructive solid geometry techniques to form more complex objects. Each cell is composed of a nested structure including different membranes representing the cell wall (cellulose + hemicellulose + lignin = CHL), the pigments (chlorophyll a+b), and the vacuole (water). The size and shape of the cells are explicitly described. Each medium is characterized by an index of refraction and an absorption coefficient to describe the partitioning of light among the reflected, transmitted, or absorbed contributions. The spectral dependence of these values for the different media are defined. The properties of pure liquid water are used [6] for the cytoplasm. The refractive index of cell walls is provided by the PROSPECT model [7]. The specific absorption coefficient of chlorophylls has been determined by [8], who also assessed the specific absorption coefficient of CHL using dry leaves. As hypothesized by [9], pigment particles immersed in the cytoplasm have practically the same refractive index as their environment. In consequence, we will assume that the refractive index of chlorophyll is the same as that of water.

3 Description of the ray tracing code

Radiation transfer in this simulated three-dimensional leaf is computed with a Monte Carlo ray tracing code called Raytran and based on the latest computer graphics techniques. It is designed to investigate radiation transfer problems in terrestrial environments over a variety of spatial scales [10], [11]. Incident rays are either direct and/or diffuse to represent different laboratory lighting conditions. Photons are generated in the forward direction, *i.e.*, from the light to the scene, and tracked from collision to collision throughout the leaf cell structure until the ray is absorbed or escapes from the leaf. The reflectance of a membrane (R) is calculated with the Fresnel formulae using the refractive indices of the current medium and of the membrane [12]. The ray is specularly reflected if $u_1 \leq R$

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where u_1 is a random number uniformly distributed in $[0,1]$, otherwise the ray is refracted in the direction determined by the Snell cosine law. The probability that the ray is absorbed by a medium is defined by the Beer's law. The ray is absorbed if $a^{-1}\log u_2 < d_m$, where d_m is the maximum distance that the ray may travel within the membrane, a is the absorption coefficient of the medium and $u_2 \in [0,1]$. Ray paths statistics are accumulated to compute the bidirectional reflectance and transmittance, but also the light extinction profile inside the leaf.

4 Simulation of leaf spectral and directional properties

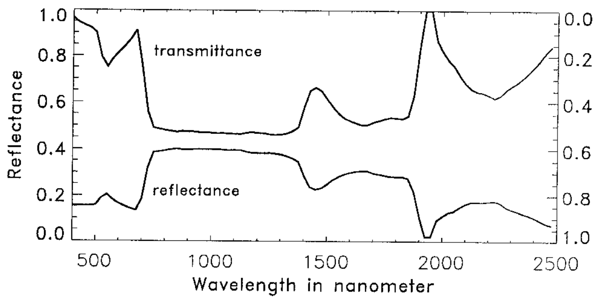

Figure 1: Leaf hemispherical reflectance and transmittance. The vertical distance between the two curves represents the absorptance.

We first calculated the leaf hemispherical reflectance and transmittance over the 400 to 2500 nm region. The upper face of the leaves is illuminated by a punctual and isotropic light source. Fig.1 shows classical absorption features in the visible and middle infrared.

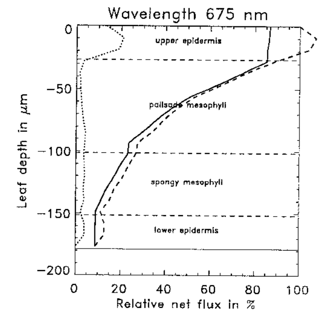

Figure 2: Relative fluxes perpendicular to the leaf surface: net flux (solid line), downward flux (dotted line), upward flux (dashed line).

At each wavelength, it is also possible to calculate the upward (transmitted), downward (scattered), and net flux for different positions along a vertical axis inside the leaf. As many as twenty virtual sensors were regularly positioned between the two epidermal layers. Each time a photon reached the upper surface of the sensor, the downward flux counter was incremented by 1; and conversely, the upward flux counter was incremented when a photon reached its lower surface. Photons collected in this manner were then divided by the total number of emitted photons to provide relative energy fluxes. For each sensor, the net flux was calculated as the difference between the downward and upward fluxes. Fig.2 illustrates the light gradients within the leaf at 675 nm. The distribution of light shows several notable features in accordance with experimental results obtained by [13] using a fibre-optic probe. For instance, these authors showed small rises in the profiles when a transition between two different tissues occured; these rises, which were probably due to optical discontinuities, can be seen in Fig.2. The attenuation of transmitted light is exponential indicating significant amounts of absorption. 80% of the light is absorbed in the palissade, *i.e.*, within the initial 90 μm or so of the leaf. The reason why the relative downward flux in the upper epidermis is higher than 100% is that the same photon may be scattered several times inside an epidermal cell and then be counted more than once by a detector. This concentration of light has been already reported in the literature for various leaves [14]. Fig.2 also shows that the amount of scattered light falls to less than 10% of its initial level within the upper epidermis, as observed by [13].

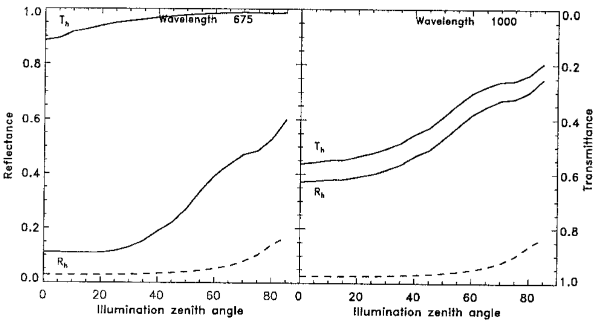

Figure 3: Hemispherical reflectance R_h, transmittance T_h, and single scattering reflection R_h^s (dashed line) for various IZA.

The relationship between the hemispherical reflectance R_h, or transmittance T_h, and the illumination zenith angle (IZA) assuming direct radiation has been also investigated. Results for 675 nm and 1000 nm are presented in Fig. (3). In the red, only R_h significantly varies with the IZA. In the NIR, both R_h and T_h present a zenital dependence which is symmetric so that the hemispherical absorptance is constant. Using the Fresnel equations and an average refractive index of 1.45 characteristic of leaf material, [15] calculated the reflection of light by a dielectric surface in three dimensions and found similar results for R_h^s. As the hemispherical single scattering reflection results only from the surface reflection, it should be also comparable with experimental measurements of the polarized reflectance of plant leaves such as those performed by [16]. Because Raytran ignores for the moment the effects of the cuticular waxes, of the leaf pubescence which may produce diffraction and increase R_h, our values are relatively low but still consistent.

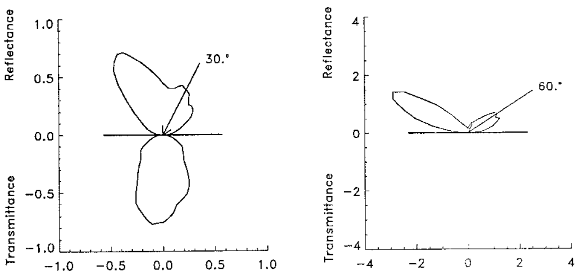

Figure 4: Bidirectional reflectance and transmittance in polar coordinates for an illumination angle of 30°(left) and 60°(right).

Finally, we simulated the bidirectional reflectance and transmittance for various IZA in the NIR (Fig.4). The specular component for the reflectance increases as the IZA becomes higher while the transmittance is rather Lambertian. These results agree with observations [17], [18].

5 Conclusion

This study is the first attempt to simulate light scattering and absorption with a ray tracing model in a three-dimensional leaf where the position, size and shape of each cell are explicitly defined. In terms of leaf biophysical properties, we provided a reasonable description of the internal structure for a typical dicotyledon leaf described with simple geometric volumes filled by three different media: cells walls (CHL), chlorophylls, and water. Reasonable concentrations of the leaf biochemical components were also found. The raytran model allows to simulate spectral and bidirectional properties of the leaf. Although the model is in its early stage, the results obtained agree fairly well with observations. From a physiological point of view, it would be interesting in the future to examine the light harvesting consequences of various leaf structures and chemical compositions. Such studies may prove very useful to understand ecological processes.

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