Multispectral and multiangular measurement and modeling of leaf reflectance and transmittance

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ABSTRACT - *Radiative transfer models are useful to non-destructive estimation of vegetation biochemical content both at leaf level and canopy level. They generally regard the leaf as a plane parallel absorbing and scattering medium, the absorption coefficients of which are often estimated by model inversion. This study aims at predicting leaf optical properties without resort to model inversion. A typical dicotyledon leaf, the biochemical content and anatomy of which have been measured in the laboratory, acts as a model for 3-D geometrical reconstruction. The assigned absorption coefficients and refractive indices of constituents are compared to values published in the literature. Radiative transfer simulations in the leaf model are run with the 3-D Monte-Carlo ray-tracing model RAYTRAN. Simulated reflectance and transmittance reproduce well typical leaf spectral features. The anisotropy in the bidirectional simulations is also close to measurements. However, the model simulations overestimate the measured reflectances at large illumination zenith angles. This may be due to the prescription of too high values for the cell wall refractive index and excessive air layers between the leaf palisade and the upper epidermis in the 3-D leaf model.*

1. INTRODUCTION

Plant leaves are the main organs of photosynthesis. Their anatomy has adapted to this role, leading to particular optical properties (Gausman 1985). Leaf structure and biochemical content determine their reflectance, transmittance, and absorptance properties. The spectral variations are explained by absorption features of photosynthetic pigments (mostly chlorophylls), water (the main leaf constituent) and dry matter (cellulose, hemicellulose, lignin, etc.) (Jacquemoud *et al.* 1996). Directional properties are associated with the numerous air spaces within the leaf blade causing isotropic scattering and with surface roughness affecting the specular reflection of light (Woolley 1971). Leaf radiative transfer models are useful for studies in remote sensing of vegetation or plant physiology. The leaf may be regarded as a stack of plane parallel absorbing plates (Jacquemoud and Baret 1990) or as a scattering and absorbing medium (Yamada and Fujimura 1991). In both cases absorption coefficients are determined from model inversion in order to fit measured reflectance and transmittance data. We aim at predicting leaf optical properties without resorting to model inversion. The three-dimensional leaf model is inspired by a European beech leaf (*Fagus sylvatica L.*) picked in July 2005 and shown in Fig. 1. This dicotyledon is a dominant tree species in France since it constitutes about 10% of French forests.

Figure 1: Photo of the European beech leaf.

This paper is based on laboratory measurements presented in Section 2. A spectrogoniophotometer has been designed to measure the leaf bidirectional optical properties in the wavelength range from 500 nm to 880 nm at 4 incidence angles and in 200 viewing directions. The water, dry matter and chlorophyll contents have been determined using destructive methods. We observed the leaf three-dimensional structure through an optical microscope to measure the cell size and air fraction of each tissue. Section 3 decribes the steps followed to derive directional-hemispherical reflectance and transmittance values from bidirectional measurements. A virtual three-dimensional leaf was reconstructed using the cross sections (Section 4) and its optical properties were studied with ray-tracing techniques (Section 5). Both the directional-hemispherical and bidirectional reflectances, together with the transmittances, have been simulated and compared to our measurements. Absorption profiles are also provided.

2. MEASUREMENT OF LEAF OPTICAL AND ANATOMICAL PROPERTIES

The European beech leaf is put in a spectrogoniophotometer (Fig. 2) to determine its Bidirectional Reflectance and Transmittance Distribution Functions (BRDF and BTDF, respectively) as defined in Nicodemus *et al.* (1977). These functions can be assessed using a Spectralon® reference panel calibrated to account for its deviation from Lambertian behaviour (Combes *et al.* 2006):

$$BRDF_{leaf} = \frac{Radiance_{leaf}}{Radiance_{Spectralon}} BRDF_{Spectralon} \qquad [1]$$

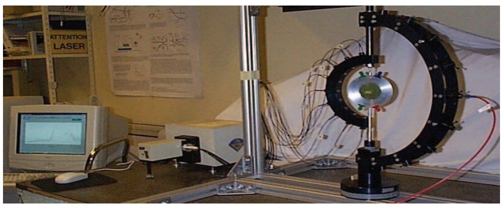

Figure 2: Spectrogoniophotometer measuring reflected and transmitted light at 4 illumination directions, 200 viewing directions, and 381 wavelengths from 500 nm to 880 nm.

Measured BRDF and BTDF (expressed in sr^{-1}) are plotted in Fig. 3 in polar coordinates. The zenith viewing angle is proportional to the radial coordinate *r* and the azimuth viewing angle is equal to the angular coordinate θ. The incident direction and the viewing directions are marked by a black star and black dots, respectively.

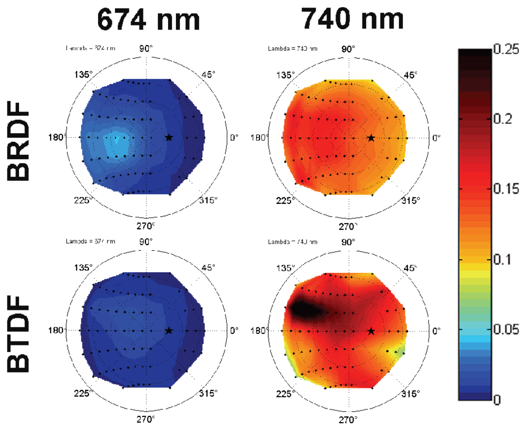

Figure 3: Polar plots of the measured BRDF (top panels) and BTDF (bottom panels) in the red (left panels) and near-infrared (right panels) at 25° zenith illumination angle. BRDF and BTDF units are sr^{-1}.

Immediately after the optical measurements, three fragments of the leaf tissue were sampled for biochemical and anatomical structure measurements: chlorophyll content, water and dry matter contents, and leaf cross-section. Biochemical contents are presented in Tab. 1 and the cross-section in Fig. 4.

Water content $(g.cm^{-2})$	6.2×10^{-3}
Dry matter content $(g.cm^{-2})$	5.8×10^{-3}
Chlorophyll content $(g.cm^{-2})$	4.2×10^{-5}

Table 1: Leaf biochemical content measured in the laboratory by destructive methods.

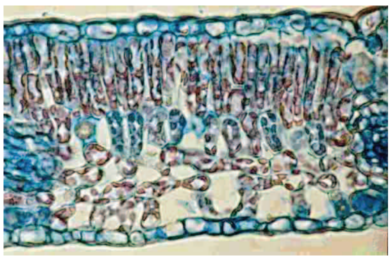

Figure 4: Leaf cross-section (height 120 µm, width 200 µm, thickness 8 µm, stained by astrablue 0.5% aq. and Ziehl-Neelsen carbolfuchsin 10%).

3. ESTIMATION OF HEMISPHERICAL OPTICAL PROPERTIES

The Directional Hemispherical Reflectance and Transmittance Factors (DHRF and DHTF, respectively) are obtained by integration of the corresponding bidirectional quantities:

$$DHRF(\lambda) = \iint BRDF(\lambda, \theta, \varphi) \cos\theta \sin\theta \, d\theta \, d\varphi \qquad [2]$$

Because the BRDF are not accurately measured at all viewing directions, especially at high angles, it is convenient to fit a BRDF model to the measurements before integrating. Bousquet et *al.* (2005) developed such a model which assumes the BRDF to be the sum of a diffuse component and a specular component. The specular component depends upon two wavelength-independent parameters: the surface effective refractive index n and the surface roughness σ. Their fitted values were 1.42 and 0.32, respectively. The model assumes that the diffuse component is not angular-dependent because the multiple scattering of photons within the leaf interior tends to redirect light equally whatever the direction. Once modeled, the BRDF can be numerically integrated using Eq. 2. The resulting reflectance spectra are shown in Fig. 5 together with the transmittance spectra. The relative error tolerance in the numerical integration is as low as 10^{-4}. However the lack of data at grazing viewing angles and in the specular lobe is the main cause of uncertainty.

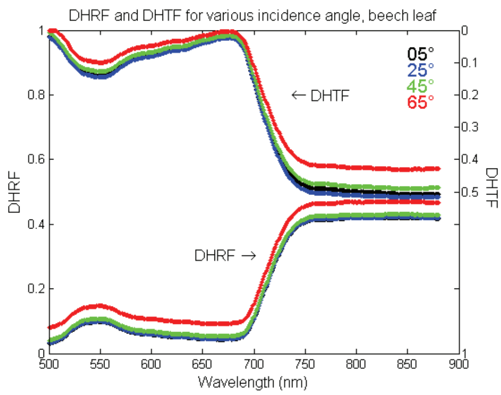

Figure 5: Leaf DHRF (scale on the left) and DHTF (scale on the right) calculated on the basis of bidirectional measurements and the appoach of Bousquet *et al.* 2005.

4. CONSTRUCTION OF THE LEAF MODEL

The 3-D geometric model of the European beech leaf shown in Fig. 6 was built based upon its cross-section (Fig. 4) and its biochemical content (Tab. 1). The cell shapes and dimensions of each tissue were set to agree with the measured leaf anatomy and biochemistry. The main characteristics of the leaf model are shown in Tab. 2. The chlorophyll and dry matter contents are the same in Tabs 1 and 2. The water content is about 50% lower in the model than in the real leaf in spite of true thicknesses for each tissue, showing that the leaf model is not compact enough and contains too many air spaces. Fortunately water has little influence on the absorption of light in the visible and near-infrared domains.

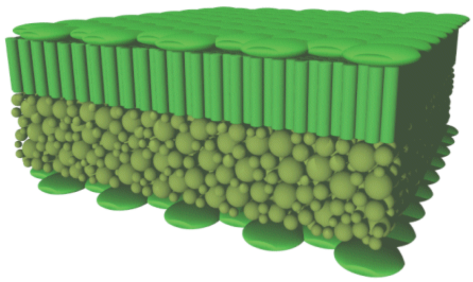

Figure 6: 3-D leaf model.

	Water	Dry matter	Chlorophyll
Content ($g\,cm^{-2}$)	3.7×10^{-3}	5.8×10^{-3}	4.2×10^{-5}
Density ($g\,cm^{-3}$)	1	1.5 Jacquemoud *et al.*1996	0.047 Fukshansky *et al* 1993
Refractive index	1.33 *at* 700 *nm* Segelstein 1981	1.52 (VIS) Kumar and Silva 1973	1.42 (VIS) Kumar and Silva 1973
Linear absorption coefficient	Segelstein 1981	from Prospect	cf figure

Table 2: Leaf model parameters.

Each leaf constituent is optically described for each wavelength by a refractive index and a linear absorption coefficient. The specific absorption coefficient of chlorophyll is actually the most important because it drives the absorption in the PAR (Photosynthetically Active Radiation) region. It is represented by a sum of Gaussian functions and compared with values taken from the relevant literature (Fig. 7). The specific absorption coefficients of water and dry matter were directly taken from Segelstein (1981) and from the PROSPECT model (Jacquemoud and Baret 1990), respectively, but their influence in the PAR region was insignificant.

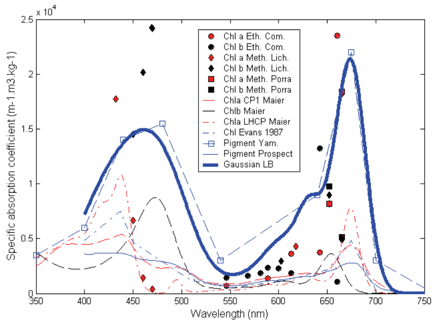

Figure 7: Modeled specific absorption coefficient of chlorophyll (thick blue line) and values from the literature (thin lines and dots).

The density ρ (g cm^{-3}) was used to derive linear absorption coefficients α (cm^{-1}) from specific absorption coefficients K (cm^2 g^{-1}) for each constituent i:

$$\alpha_i = K_i \times \rho_i \qquad [3]$$

It was also used to derive the volume V from the mass m for a unit leaf area:

$$V_i = m_i / \rho_i \qquad [4]$$

Values for ρ and n were taken from the literature (see Tab. 2).

5. SIMULATION OF THE RADIATIVE TRANSFER

In accordance with the approach of Govaerts *et al.* (1996), the extensively benchmarked (e.g., Pinty et *al.* 2001, 2004) 3-D Monte-Carlo ray-tracing model RAYTRAN (Govaerts and Verstraete 1998) was run to simulate:

- the DHRF and DHTF at four illumination zenith angles {5°,25°,45°,65°} and fourteen selected wavelengths spanning the 400–2400 nm range (Fig. 8),
- the BRDF and BTDF at highly (674 nm) and poorly (740 nm) absorbed wavelengths at 25° illumination zenith angle (Fig. 9),
- the light flux profile in the leaf at 674 nm and 0° illumination zenith angle (Fig. 10).

Simulated DHRF and DHTF reproduce well typical leaf spectra at small incidence angles (Fig. 8). The DHRF increases while the DHTF decreases when the incidence angle increases, as experimentally observed in the laboratory (Fig. 5). However, at large illumination zenith angles, the reflection is overestimated due to injustified air spaces between the upper epidermis and the palisade layer, and to high refractive index values of the dry matter. In particular the air layer between these two tissues should be reduced at the most or filled with water. Future expansions of this work will hopefully relieve this situation.

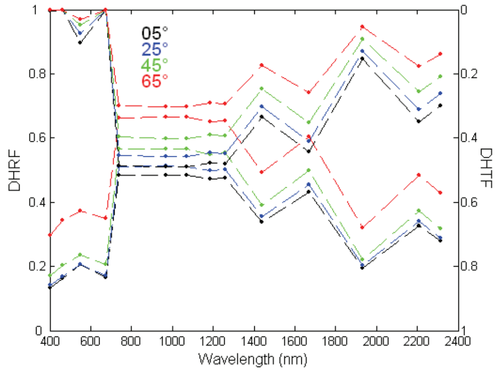

Figure 8: Simulated DHRF and DHTF at {5°,25°,45°,65°} illumination zenith angles across the 400–2400 nm spectral domain.

The simulation of the leaf bidirectional optical properties (Fig. 9) shows a strong specular reflectance while the transmittance is almost Lambertian, whatever the wavelength. As for the DHRF, the surface reflection is overestimated due to the high refractive index of cell walls. Note that the BTDF maxima are observed at 0° viewing zenith angle although the illumination zenith angle is set to 25°, indicating that the leaf structure partly redirects light in the direction perpendicular to the leaf blade.

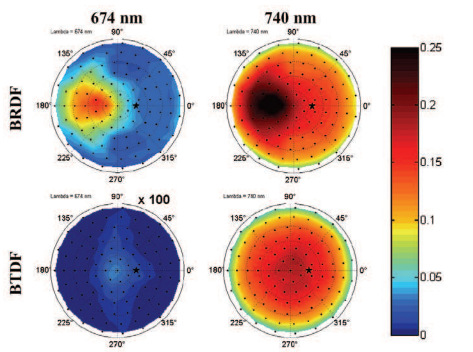

Figure 9: Polar plots of the simulated BRDF (top panels) and BTDF (bottom panels) in the red (left panels) and near-infrared (right panels). BRDF and BTDF units are sr^{-1}. The leaf is illuminated at 25° zenith angle.

The decrease of net downward flux in the leaf (Fig. 10) is faster in the spongy layer than in the palisade although chlorophyll content is about twice higher in the palisade. This is attributed to the greater diffuseness of light fluxes in the spongy layer. Diffuseness is thus essential to the efficiency of absorption.

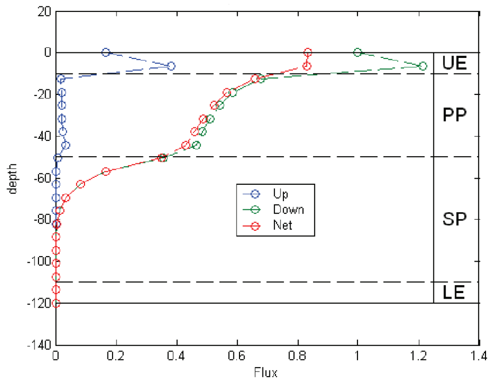

Figure 10: Simulated light flux within the leaf at 0° illumination zenith angle and 674 nm. UE, PP, SP and LE stand for Upper Epidermis, Palisade Parenchyma, Spongy Parenchyma and Lower Epidermis, respectively.

6. CONCLUSION

This study shows the potential of three-dimensional radiative transfer simulations to understand the interaction of light with plant leaves. It is now possible to build 3-D geometrical leaf models from microscope observations and to test these interactions using ray-tracing codes. Efforts should be made regarding the optical properties of leaf constituents such as chlorophyll specific absorption coefficient which depends on the geometry of light fluxes. Results of this study may be used to improve analytical models of leaf radiative transfer used by the vegetation remote sensing community.

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