Leaf BRDF and BTDF Measurements and Model

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Abstract: The spectral and bidirectional optical properties of plant leaves are measured in the visible - near infrared spectrum (500 - 880 nanometers) by using a spectro-photo-goniometer. Leaf biochemistry and anatomy are estimation by model inversion and compared with laboratory measurements.

1. Introduction

The remote estimation of the biochemical content of plant leaves is based on the detection of their spectral signatures in the outgoing light. Whatever the leaf, part of the incident light is always reflected without interaction with the constituents of interest. If not quantified, this surface reflection may be a source of error in the estimation of the leaf chlorophyll or water contents, for instance. Moreover, when understood and measured, it can provide some new information about the state of the leaf surface. Two approaches have been proposed in the literature to distinguish between surface reflection and volume reflection which are always mixed together. The first one measures the degree of polarization of the reflected light, which depends on whether the light has penetrated inside the leaf or not (Vanderbilt and Grant, 1986). The second one, that we chose in this paper, measures the spectral and bidirectional reflectance and supposes that the surface reflection does not depend on the wavelength contrary to the volume reflection (Bousquet et al., 2005). It requires a spectro-photo-goniometer to sample the bidirectional and spectral reflectance of leaves and an appropriate physical model.

In this paper, we present the preliminary results of an experiment which aims at testing the ability of such tools to supply reliable estimations of leaf anatomy and biochemistry. At first, the Bidirectional Reflectance (BRDF) and Transmittance (BTDF) Distribution Functions of various leaf samples selected so as to cover a wide range of foliar structures are analysed, as well as their corresponding hemispherical integrated expressions, the Directional Hemispherical Reflectance (DHRF) and Transmittance (DHTF) Factors. In a second step, the PROSPECT model and a leaf BRDF model inspired by the Cook-Torrance equations to account for the surface reflection are inverted. The estimated quantities are compared to independent measurements.

2. Experimental Measurements

The optical properties, biochemical content, and anatomical characteristics of plant leaves have been measured in July 2005 on various species: Monocots like fescue grass (*Festuca arundinacea*) and corn (*Zea mays*), and Dicots like beech (*Fagus sylvatica*), vine (*Vitis vinifera*), soybean (*Glycine max*), laurel (*Prunus laurocesarus*), and walnut (*Juglans regia*). Their BRDF and BTDF were acquired using a spectro-photo-goniometer designed for this purpose, each nanometer from 500 to 880 nm, in four illumination zenith angles {5°, 25°, 45°, 65°} and in 98 viewing directions. The BRDF is defined as the ratio of the radiance R of the illuminated face measured in the direction (θ_v φ_v) and the solid angle $d\Omega$ to the irradiance I in the direction (θ_s φ_s) (Nicodemus et al., 1977):

$$BRDF(\lambda,\theta_s,\varphi_s,\theta_v,\varphi_v,d\Omega)=\frac{R_{\text{illuminated face}}(\lambda,\theta_v,\varphi_v,d\Omega)}{I(\lambda,\theta_s,\varphi_s)} \tag{1}$$

φ_s is set to zero and will not be mentioned hereafter. The output signal measured by the spectro-photo-goniometer is proportional to the radiance of the target. When the irradiance and configuration are maintained constant, the ratio of the leaf signal to the reference signal (Labsphere Spectralon) permits the calculation of the leaf BRDF:

$$BRDF_{\text{leaf}}=\frac{R_{\text{illuminated face}}}{R_{\text{spectralon}}}BRDF_{\text{spectralon}} \tag{2}$$

The Spectralon is assumed to be Lambertian, i.e., its BRDF is constant and equal to $1/\pi$ steradian^{-1}. The BTDF is obtained in the same way by considering the radiance of the non-illuminated face in Eq. (1) and (2).

Immediately after the optical measurements, fragments of leaf tissue were sampled to determine their biochemical content: chlorophyll a+b, water, and dry matter. The chlorophyll content (expressed in µg cm^{-2}) was estimated in two ways for comparison: non-destructively using a calibrated SPAD-502 (Minolta) chorophyll-meter and by extraction in a solvent (the data are not yet available). Water content (expressed in g cm^{-2} or cm) and dry matter content (expressed in g cm^{-2}) were calculated by weighing one disc of 14 mm in diameter of fresh and dry samples of leaf material. The leaf anatomical characteristics will be evaluated later on by microscope observations on samples preserved for this purpose.

3. Data Analysis

Fig. 1 and 2 present the measured BRDF and BTDF of an adaxial beech leaf face at λ = 680 nm for four angles of incidence θ_s: {5°, 25°, 45°, 65°} marked by a star on the plot. As expected, the BRDF are not Lambertian: they show a large anisotropy which varies with θ_s. The maxima are 0.03 steradian^{-1} at θs = 5° and 0.45 steradian^{-1} at θs = 65°, i.e. 15 times greater. This is due to the strong specular reflection at the leaf surface. The shapes of the BTDF are much more Lambertian and they roughly remain the same whereas their magnitude decreases when the angle of incidence increases.

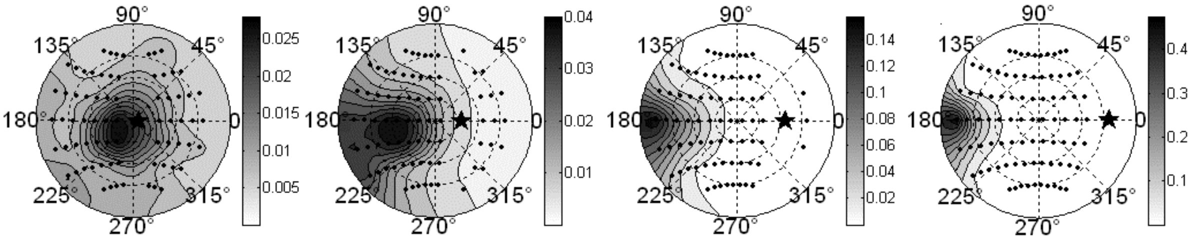

Figure 1: Polar plot of the BRDF (steradian^{-1}) of an adaxial beech leaf face at 680 nm for four incidence angles {5°, 25°, 45°, 65°}.

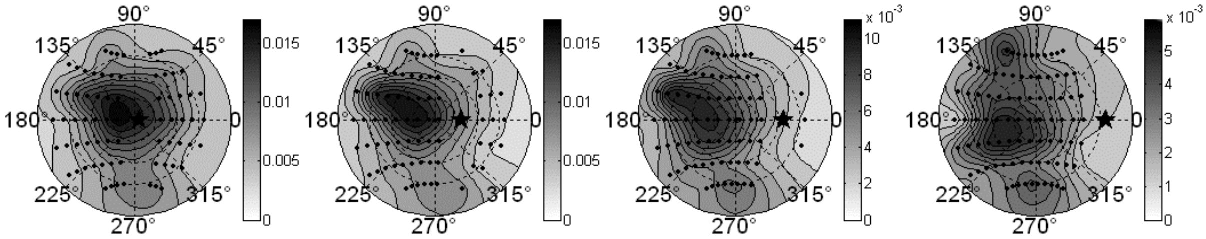

Figure 2: Polar plot of the BTDF (steradian^{-1}) of an adaxial beech leaf face at 680 nm for four incidence angles {5°, 25°, 45°, 65°}.

These results compare well with the literature (Walter-Shea et al., 1989; Brakke, 1994).

From the measured BRDF and BTDF one can derive the hemispherical reflectance (DHRF) and transmittance (DHTF) which are obtained by summation over the upper hemisphere, for instance:

$$DHRF(\lambda,\theta_s) = \sum_i BRDF\left(\lambda,\theta_s,\theta_v,\varphi_v,d\Omega_i\right)\cos\theta_v d\Omega_i \qquad (3)$$

The estimation of these quantities is accurate for Lambertian BRDF or BTDF but it deteriorates with increasing anisotropy. Fig. 3 shows the DHRF and DHTF of the beech leaf at four angles of incidence. The DHRF are similar whatever the angle of incidence but the high anisotropy of the BRDF at 45° and 65° (Fig. 1) is likely to cause an underestimation. The DHTF obviously decrease with the angle of incidence as observed by Walter-Shea et al. (1989).

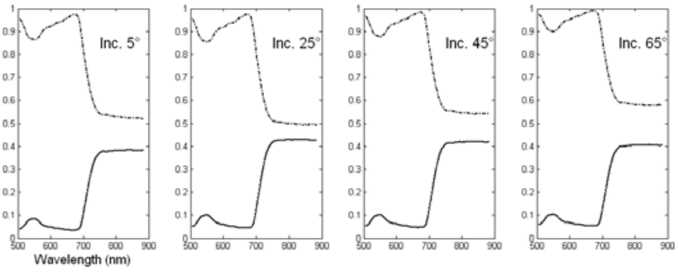

Figure 3: Beech DHRF (solid line) and DHTF (dotted line, reverse scale) as a function of the wavelength at four angles of incidence.

Leaf reflectance and transmittance spectra acquired at low incidence angle by a spectrophotometer equipped with an integrating sphere can be used to estimate the leaf chlorophyll content. The inversion of PROSPECT on the DHRF and DHTF permits the retrieval of the leaf biochemical content. The measured and modeled DHRF and DHTF of three leaves are shown in Fig. 4 while the estimated chlorophyll contents are gathered in Tab. 1.

Table1: Estimated chlorophyll content (µg cm^{-2}).

Leaf	SPAD signal	SPAD chlorophyll	PROSPECT chlorophyll
Beech	39.8	43.1	43.7
Soybean	35.2	35.9	35.5
Laurel	63.3	77.6	64.2

The relative difference between the two methods range from 1% for soybean to 20% for laurel. Note that it increases with the chlorophyll content due to saturation problems of the SPAD signal at high concentrations.

Bousquet et al. (2005) used a geometric optics model to simulate the leaf BRDF assuming that the BRDF is the sum of two components. The specular component $BRDF_{spec}$ which represents the specular reflection at the leaf surface is anisotropic and wavelength independent. The diffuse component which corresponds to all the non-specular reflection is Lambertian and wavelength dependent. For a single wavelength λ the model input parameters are the Lambert coefficient k_L, the leaf surface refractive index n, and the leaf surface roughness σ:

$$BRDF(\lambda) = k_L(\lambda)/\pi + BRDF_{\text{spec}}(n,\sigma) \qquad (4)$$

This model has been inverted on the beech BRDF for 380 wavelengths, the four angles of incidence {5°, 25°, 45°, 65°} and 65 viewing zenith angles. Results are shown in Fig 5. The spectral variation of k_L is marked by the absorption features of plant biochemicals because it represents the part of reflected light that enters into the leaf. As for the specular component, σ does not vary with the wavelength ($\sigma \approx 0.35$) and n is constant in the visible ($n \approx 1.5$) and, at a lower level, in the near infrared ($n \approx 1.3$) which confirms our assumptions. Later on,

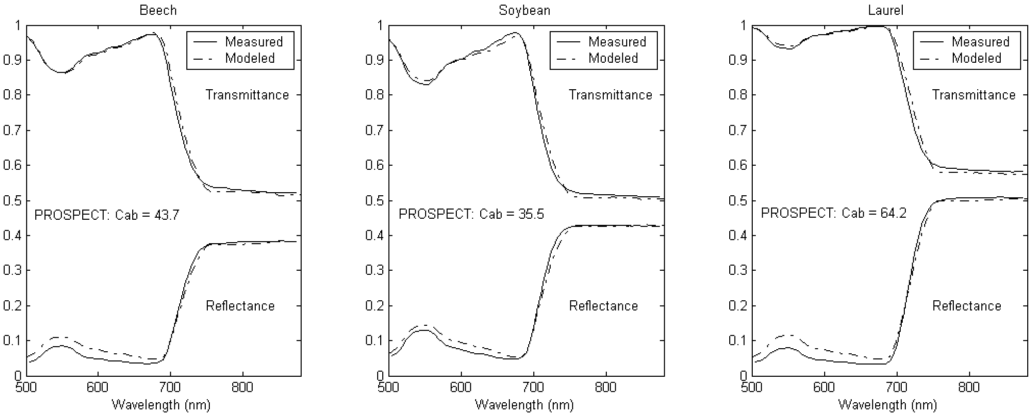

Figure 4: Measured and modeled DHRF(5°) and DHTF(5°) of three different leaves.

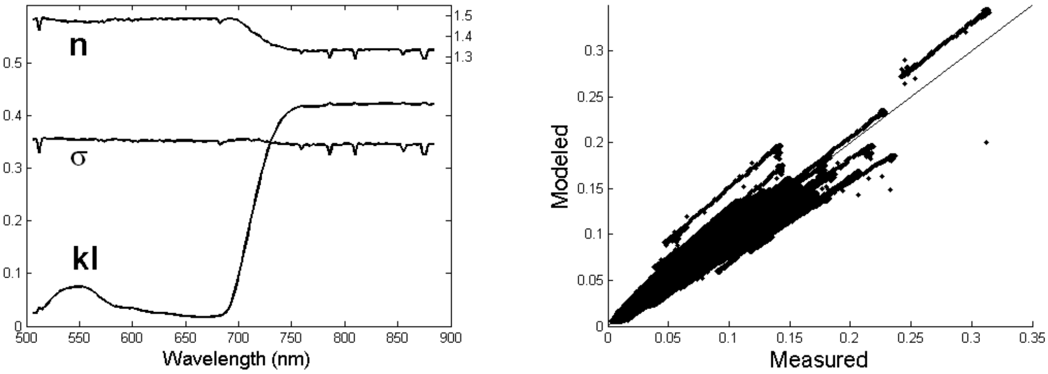

Figure 5: Three parameter model inversion at each wavelength for beech. Left: parameters values as a function of wavelength. Scale for k_L and σ on the left, for *n* on the right. Right: measured vs modeled BRDF.

these values will be compared with microscope observations of leaf cross-sections.

4. Conclusion

There is a shortage of studies concerning leaf bidirectional optical properties and their modeling. This paper provides new and accurate measurements of leaf BRDF and BTDF in the continuous spectrum between 500 nm and 880 nm. Models are used to estimate leaf surface features as well as biochemical contents. They are still under development and further work should lead to a validated leaf spectral and directional optical properties model.

Acknowledgment

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References

[1] Bousquet, L., Lachérade, S., Jacquemoud, S. and Moya, I. (2005). Leaf BRDF measurements and model for specular and diffuse components differentiation. *Remote Sensing of Environment*, In press.

[2] Brakke T.W. (1994), Specular and diffuse components of radiation scattered by leaves, *Agricultural and Forest Meteorology*, 71(3-4):283-295.

[3] Nicodemus, F. E., Richmond, J.C., Ginsberg, I.W. and Limperis, T. (1977). *Geometrical Consideration and Nomenclature for Reflectance*. NBS Monograph. NBS MN-160. 52 pp. October 1977.

[4] Vanderbilt V.C. and Grant L. (1986), Polarization photometer to measure bidirectional reflectance factor R(55°,0°;55°,180°) of leaves, *Optical Engineering*, 25(4):566-571.

[5] Walter-Shea E.A., Norman J.M. and Blad B.L. (1989), Leaf bidirectional reflectance and transmittance in corn and soybean, *Remote Sensing of Environment*, 29(2):161-174.

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