LEAF OPTICAL PROPERTIES: A STATE OF THE ART

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ABSTRACT – Although leaf optical properties encompas an extensive subject, reviews are rare and generally tackle questions closer to plant physiology than remote sensing. Different ways these properties are measured and used in inversion models to estimate leaf biophysical properties are described in this paper. We examine critically the most common methods according to the type of leaf material (broad leaves or needles), to the available measurements, and to the ensuing applications.

1 - INTRODUCTION

This paper is intended to review the state-of-the-art of a domain that is of prime interest to optical remote sensing. As leaves represent the main surfaces of plant canopies where energy and gases are exchanged, their optical properties are essential to understanding the transport of photons within vegetation. Because of the importance of photosynthetic function, leaf optical properties have been the subject of hundreds of studies since the middle of the last century. The applications of such studies are numerous, from plant physiology (photosynthesis, photomorphogenesis) to remote sensing in the optical domain (environmental studies, precision farming, ecology). Most papers have focused on the leaf spectral properties (hemispherical reflectance and transmittance) in connection with their biochemical content (chlorophyll, water, dry matter, etc.) and their anatomical structure. For instance, a plant stress resulting from an insect attack or a nitrogen deficiency induces degradation of the leaf chlorophyll content, which has repercussions on the leaf optical properties: the reflectance and transmittance increase over the whole visible spectrum. This relation between cause and effect allows the estimation of leaf biochemistry − the chlorophyll content in this particular case − by establishing empirical relationships between the variable of interest and the leaf reflectance or transmittance, or better still, by directly using a physical model.

Most canopy reflectance models assume leaves to be Lambertian, *i.e.,* perfect scatterers. In consequence, the bidirectional properties of leaves have received little investigation contrary to plant canopies. The specular reflection at the leaf surface, however, affects the angular distribution of light and consequently the interpretation of remote sensing data. What is the determinism of the leaf BRDF (Bidirectional Reflectance Distribution Function)? This question is unfortunately still at issue, although the surface characteristics are intuitively understood to be the main factor involved in these properties. The current generation of spaceborne sensors (MISR and POLDER for instance) which can measure the radiance of targets in several viewing angles urge the scientific community to take an interest in this aspect of leaf optical properties, as suggested by recent workshops on multiangular remote sensing. Such studies would also have broad consequences for ecophysiology where it has been proven that the directional reflectance of plant leaves may affect the development of nearby leaves.

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Finally, although this paper doesn't focus on absorption profiles within plant leaves, it nevertheless briefly tackles this issue because the introduction of chlorophyll gradients into leaf optical properties models, for instance, may improve the estimation of photosynthetic pigments by remote sensing techniques. There are direct applications for this information in precision farming, e.g., the assessment of the plant nitrogen status.

The first part of this article briefly reviews different ways for measuring leaf optical properties. In the second part, we emphasize methods that allow inference of leaf variables by optical methods.

2 - MEASURING THE LEAF OPTICAL PROPERTIES

2.1 - Spectral properties

There is a long history of measuring the directional-hemispherical reflectance ρ_λ and transmittance τ_λ of plant leaves by laboratory spectrophotometers equipped with integrating spheres to average the signal reflected or transmitted in all directions. In a single-beam instrument for instance, the leaf blade is placed at the exit port of the sphere and is illuminated directly (Fig. 1a), or at the port of entrance (Fig. 1b); another measurement made by first illuminating the sphere wall or a standard placed at the exit port of the sphere allows calculation of ρ_λ and τ_λ (Pickering et al., 1992).

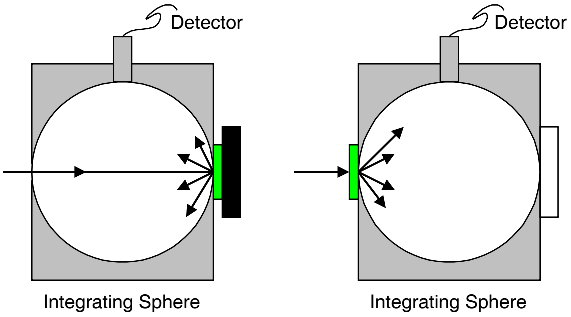

Fig. 1: Typical measurement of the directional-hemispherical (a) reflectance and (b) transmittance.

Some corrections that take into account the geometry of the sphere and its (or the standard's) optical properties are generally required to calculate absolute values. The absorptance α_λ is easily derived from ρ_λ and τ_λ through the simple relationship: $\alpha_\lambda=1-\rho_\lambda-\tau_\lambda$. Figure 2 shows typical reflectance and transmittance spectra measured on a poplar leaf (*Populus canadensis*).

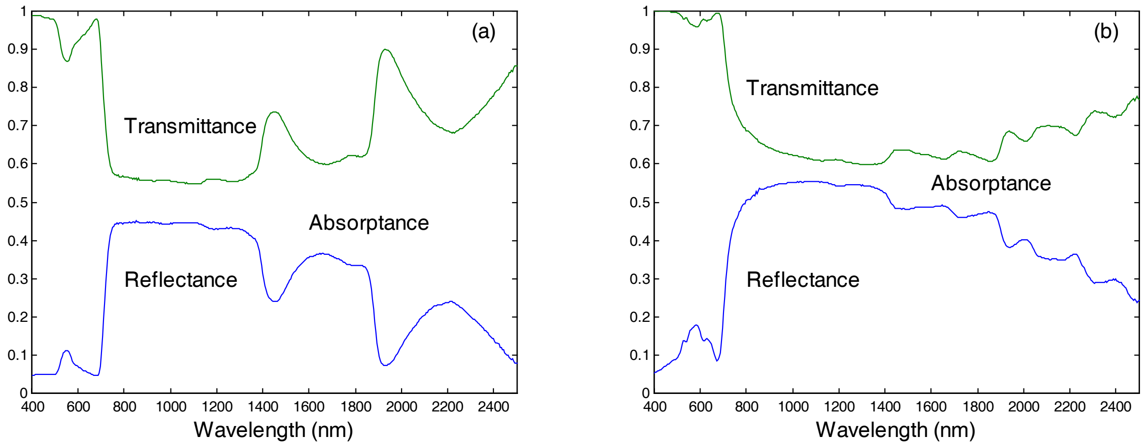

Fig. 2: Reflectance and transmittance spectra of (a) fresh and (b) dry poplar leaves

In addition, the reflectance of optically thick samples $\rho_{\lambda i}$ can be measured by stacking leaves in order to magnify the radiometric signal and to minimize the leaf-to-leaf variability or, in the case of needles or powders, by placing them in a glass cuvette. Additional corrections are required to account for multiple reflections between the sample and the glass wall (Jacquemoud et al., 1995).

The optical properties of needles must be considered separately because of difficulties of measurement. They are paradoxically, still obscure, as pointed out by the few studies reported in the recent literature. However, more emphasis is needed to resolve these problems because conifers represent a significant fraction of forest ecosystems. The size of needles is generally shorter than the diameter of the sample port of integrating spheres, which is one of several measurement problems. One technique consists of making a mat of needles arranged side-by-side into a single layer when vertical measurement is possible (Dawson et al., 1998b). As standard spectrophotometers do not allow samples to be positioned horizontally, needles must be maintained vertically by a transparent tape (Daughtry et al., 1989; Williams, 1991) or some other device. Once again, some specific corrections are required to provide reflectance and transmittance spectra. Another technique consists in measuring the infinite reflectance $\rho_{\lambda i}$ of needles contained in a glass cuvette.

In some situations, like a remote field experiment, laboratory measurements are inconvenient. It is however possible to substitute an integrating sphere interfaced to a portable spectrometer for a laboratory spectrophotometer. In the absence of an adapted instrument, a field spectroradiometer can been used to measure bidirectional reflectance by measuring leaf reflectance alternately with a black background and a white background. A simple calculation allows one to derive both the bidirectional reflectance and transmittance (Miller et al., 1992) but not directional-hemispherical as obtained in most laboratory studies. This method is a stopgap solution, strongly dependent on the measurement conditions.

Hundreds of papers already detail the variation in spectral properties in relation to leaf biochemical composition and structure, which depends on many factors like the plant species, the developmental or microclimate position of the leaf on the plant, whether it is stressed or not, etc. In this review, we consider the optical domain ranges from 400 nm to 2500 nm and is divided into three parts: the visible (400-800 nm) characterized by a strong absorption of light by photosynthetic pigments in a green leaf; the near infrared plateau (800-1100 nm) where absorption is limited to dry matter but where multiple scattering within the leaf, related to the fraction of air spaces, i.e., to the internal structure, drives the reflectance and transmittance levels; the middle infrared (1100-2500 nm) is also a zone of strong absorption, primarily by water in a fresh leaf and secondarily by dry matter when the leaf wilts. All of these observations and experimental measurements are a prerequisite for any attempt to extract biophysical information, as seen in the next part.

2.2 - Bidirectional properties

The reason for the lack of goniometers adapted to leaf BRDF (or BTDF in transmittance) measurements has been slightly touched upon in the introduction; stating that the leaf bidirectional properties are still unknown is an understatement. The first measurements of BRDF are descriptive and date from the 1960's (Tageeva and Brandt, 1960, 1961; Shulg'in et al., 1960). Breece and Holmes (1971) improved the way to acquire leaf bidirectional reflectances in several wavelengths between 375 nm and 1000 nm. However, one still waited until the late 1980's to see the first explanatory model (Brakke et al., 1989; Ma et al., 1990; Vanderbilt et al., 1990) and complete leaf BRDF measurements (Walter-Shea et al., 1989; Sanz, 1994). At the same time, some bidirectional reflectances were acquired that separated the surface from the diffuse reflectance (Grant et al., 1987, 1993; Brakke, 1994; Shuplyak et al., 1997) because the polarized fraction of light reflected on the leaf surface can be distinguished from the non-polarized fraction which entered the blade. As these measurements were performed at a single viewing angle or a few angles, Sarto et al. (1989) developed a goniometer adapted to simultaneously measure the polarized reflectance of a leaf in many directions. The one built by Pedrini et al. (1991) was designed to measure the bidirectional reflectance, transmittance, and fluorescence of plant leaves, confirming the isotropic properties of the latter. Finally, modeled after an experimental device primarily built to measure the phase function of large shaped particles like cellulose fibers or sand grains (Sasse, 1993), a new goniometer was developped by Combes et al. (2001): a beam of seven optical fibers, arranged in a semicircular arc, measures the light reflected or transmitted by a leaf in several directions simultaneously (Fig. 3a). The light is sent to a CCD camera to create an hyperspectral image in the visible / near-infrared domain. The bidirectional reflectance and transmittance are then calculated by dividing the leaf signal by the signal of a Spectralon® reference, and by applying spectral and directional corrections that account for the fact that this reference is not a perfect diffuser (Fig. 3b).

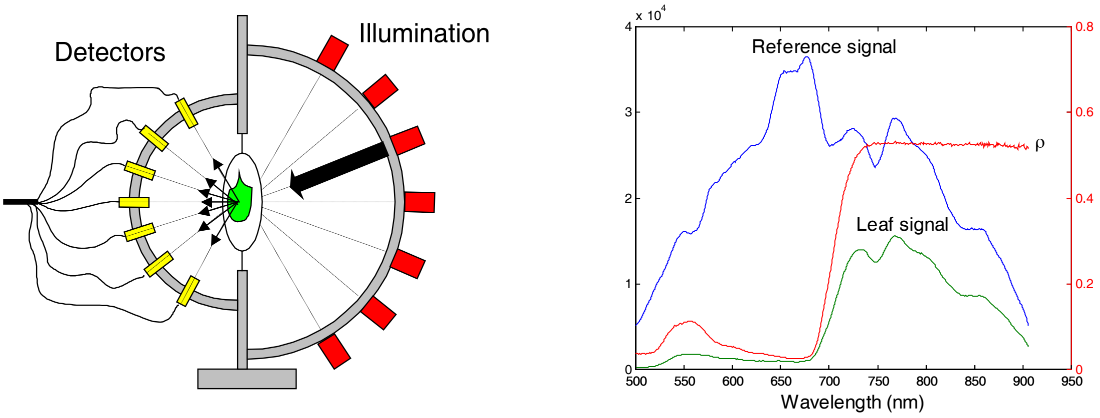

Fig. 3: Measurement of bidirectional reflectance and transmittance. a) Experimental device b) Spectral reflectance ρ of *Sorgho halepense* in the visible and near-infrared region measured for $\theta_s = 40°$, $\theta_v = 20°$, and $\varphi = 60°$ (after Combes et al., 2001).

However because most of these studies are qualitative, the question of the determinism of the leaf BRDF remains a point at issue. Computer simulations performed with Raytran (Govaerts et al., 1996), a ray tracing code designed to calculate the photon transport within different media from the leaf to the canopy level (Govaerts and Verstraete, 1998), underscored a clear relationship between the roughness of a virtual leaf and its specular behavior (Fig. 4).

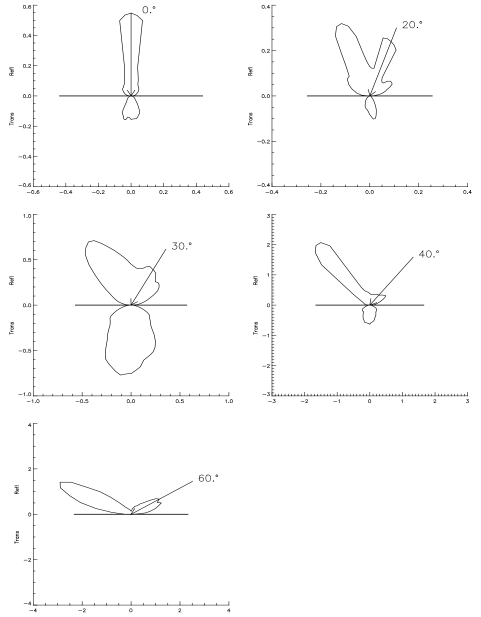

Fig. 4: Bidirectional reflectance and transmittance in polar coordinates for illumination angles of 0°, 20°, 30°, 40°, and 60° (After Govaerts et al., 1996)

2.3 - Absorption profiles

Until recently, the measurement of absorption profiles within plant leaves was more relevant to plant physiology than to remote sensing studies. For instance, recent applications in precision farming mobilized the scientific community to assess plant nitrogen status. At the leaf level, the introduction of within-leaf chlorophyll gradients into leaf optical properties models may improve the estimation of this photosynthetic pigment by remote sensing techniques.

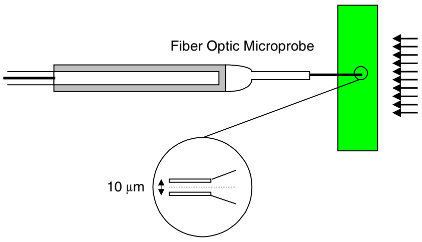

Fig. 5: Measurement of absorption profiles.

3 - EXTRACTION OF LEAF BIOPHYSICAL PARAMETERS

Leaf directional-hemispherical or bidirectional reflectance and transmittance spectra can directly feed canopy reflectance models as input parameters, but the measurement of these properties is not an end in itself. The estimation of leaf biophysical parameters developed in parallel with the estimation of canopy characteristics, often with the same methods as detailed afterwards.

3.1 - The semi-empirical approach

These consist in relating spectral indices to some characteristics of the leaf. The *combination of narrow bands* is the classical approach, like spectral vegetation indices at the canopy level. A simple relationship *f* is established between the biochemical component of interest *C* and the leaf optical properties.

$$C = f\left(\rho(\lambda_1), \ldots, \rho(\lambda_n)\right)$$

The chlorophyll concentration (Aoki et al., 1986; Yoder and Daley, 1990; Chapelle et al., 1992; Gitelson and Merzlyak, 1996; Lichtenthaler et al., 1996; etc.), and the water content (Hunt et al., 1987, 1989; Aoki et al., 1988; Inoue et al., 1993; Peñuelas et al., 1993; Ceccato et al., 2001; etc.) have been determined this way. The Minolta SPAD-502 chlorophyll meter, designed to estimate the leaf chlorophyll concentration *in situ*, is based on such an approach. However the accuracy of the estimations lacks of robustness because these relationships do not take into account the anatomical structural differences between leaves or the other pigments (carotenoids, anthocyanins, etc.) which also absorb light. *Spectral shifts*, characterized by the wavelength λ_i of the inflexion point of the red-edge region (670-780 nm), are indices specific for high spectral resolution instruments which have been used to determine chlorophyll concentrations (Horler et al., 1983; Belanger, 1990; Curran et al., 1990, 1991; Gitelson et al., 1996; etc.)

$$C_{ab} = f(\lambda_i) \text{ with } \frac{\partial^2 \rho(\lambda)}{\partial \lambda^2} = 0 \text{ at } \lambda_i$$

3.2 - The statistical approach

In this approach, leaf characteristics are determined statistically, i.e., the choice of the wavelengths or the leaf biochemical constituents is not predetermined. A first method called *spectral mixture analysis* reduces the spectral information $\rho(\lambda)$ into independent sources of variability, the endmembers. At leaf level, one considers the specific absorption coeficients $k_i(\lambda)$ of chlorophyll, water, protein, cellulose, lignin, etc. as endmembers and the coefficients C_i are the concentrations to retrieve (Goetz et al., 1990; Aber et al., 1994; Hlavka et al., 1997; etc.)

$$\rho(\lambda) = (a + b\,\lambda)\exp\left(-\sum_{i=1}^{n} k_i(\lambda) C_i\right)$$

The unknown concentrations C_i are those producing the best fit of $\rho(\lambda)$. The Hierarchical Foreground/Background Analysis (HFBA) proposed by Pinzon et al. (1998) is a more general and sophisticated spectral mixing technique equivalent to a single neuron in a neural net. Another approach is the *multiple stepwise regression analysis* which establishes a direct regression equation between leaf reflectance (or transmittance or absorptance) at a few wavelengths $\rho(\lambda_i)$, selected by the procedure, and the biochemical content of one of its constituents *C*:

$$C = \sum_{i=1}^{n} \alpha_i\, \rho(\lambda_i)$$

A restricted number of samples (calibration set) is used to determine the coefficients α_i which are tested on a larger one (validation set). Curran et al. (1992), Martin and Aber (1994), Jacquemoud et al. (1995), Yoder and Pettigrew-Crosby (1995), Bolster et al. (1996), Grossman et al. (1996), Fourty and Baret (1998), etc., obtained excellent results with this method both on fresh and dry material. The main criticism is that the selected wavelengths are not very consistent, depending on whether the regression is performed on reflectance or transmittance of fresh or dry leaves. Finally, neural networks which have become quite popular at the canopy level have potential application but have been little tested at the leaf level (Dawson et al., 1998a).

3.3 - The modeling approach

While experimental measurements of leaf optical properties were progressing, determinist models based on diverse representations of light interaction with a plant leaf were also developed. These models are distinguished by the underlying physics and by the complexity of the leaf. The simplest ones consider the blade as a single scattering and absorbing layer. In the most complicated ones, all the cells are described in detail (shape, size, position, and biochemical content). Whatever the approach, information about the refractive index and the specific absorption coefficient of leaf constituents is almost always required. Ustin et al. (1999) extensively reviewed computer-based leaf models which, from the late sixties to the present, have improved our understanding of the interaction of light with plant leaves. They can be categorized into four classes of models, in increasing order of complexity (Figure 6):

- *Plate models* (Figure 6a) which represent the leaf as one or several absorbing plates with rough surfaces giving rise to isotropic diffusion (Allen et al., 1969; Allen et al., 1970). An example of this is the PROSPECT model developed by Jacquemoud and Baret (1990), which is in widespread use in the remote sensing community. Since 1990, there has been additional improvement with the introduction of full leaf biochemistry (Fourty et al., 1996; Jacquemoud et al., 1996; Baret and Fourty, 1997) or a variable chlorophyll content within the leaf (Veyrat, 1999).
- *N-flux models* (Figure 6b) which considers the leaf as a slab of diffusing and absorbing material (Allen and Richardson, 1968; Fukshansky et al., 1991; Yamada and Fujimura, 1991; Martinez v. Remisowsky et al., 1992; Conel et al., 1993; Richter and Fukshansky, 1996).
- *Stochastic and other radiative transfer models* (Figure 6c) where the leaf is partitioned into different tissues and its optical properties simulated by a Markov chain (Tucker and Garatt, 1977; Maier et al., 1999) or a more classical approach directly based on the radiative transfer equation (Ganapol et al., 1997).
- *Ray tracing models* (Figure 6d) that require a detailed description of the internal leaf structure and the optical constants of leaf material (Allen et al., 1973; Brakke and Smith, 1987; Kumar and Silva, 1973; Govaerts et al., 1996; Baranoski and Rokne, 1997; Ustin et al., 2001).

Athough most of these models are able to accurately and coherently simulate the reflectance and transmittance of plant leaves, only radiative transfer models can be inverted by iterative methods in order to retrieve information on the leaf anatomy or biochemical constituents. It should also be noted that none of these models is adapted for needle-shaped leaves. However, Dawson et al. (1998b) recently designed a new model capable of accurately predicting the spectral response of both dried and fresh stacked pine needles. Finally, the literature is silent on the modeling of leaf bidirectional properties. The lack of leaf BRDF models is certainly constrained by a lack of experimental measurements. Nevertheless, note that research using image synthesis has brought this problem up to date (Baranoski and Rokne, 1999; Marschner et al., 1999).

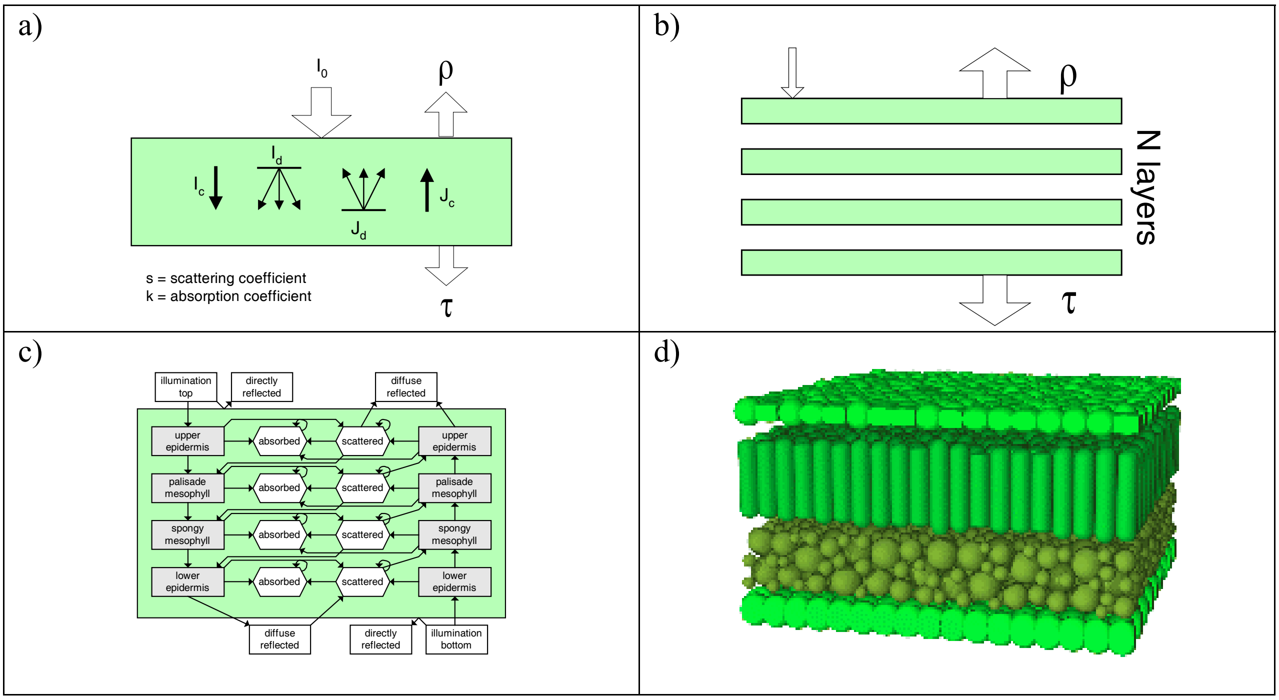

Fig. 6: Different leaf optical properties models:
(a) Plate models, (b) N-flux models, (c) Stochastic models, (d) Ray tracing models

Models are essential to understand how electromagnetic radiation interacts with leaf elements, but also to directly relate observed optical properties to leaf biophysical attributes. In the direct mode, sensitivity analyses, a crucial step in model verification and validation, ensures that the response of the computational model to the input parameters is the expected one. Recent studies based on statistical methods like the Design Of Experiments for Simulation (DOES) or the Extended Fourier Amplitude Sensitivity Test (EFAST) extend research further by quantifying the relative effects of each of the input parameters, as well as their interactions (Ceccato et al., 2001). Such information may be helpful in inversion, for instance to detect non-influential optical parameters, like the nitrogen (or protein) content in fresh leaves.

4 - CONCLUSION

Contrary to accepted dogma, much more work is required before we will completely understand leaf optical properties. This knowledge is nevertheless crucial to develop more accurate relationships between these properties and important leaf functional characteristics, or to improve models which are directly used to interpret remote sensing data when coupled with canopy reflectance models. To give an example, the separation of leaf photosynthetic pigments (chlorophyll a, b, carotenoids and xanthophylls) is still at issue, and this information would greatly improve the cartography of plant photosynthetic activity from space. Additionally, other aspects of leaf optics like fluorescence not have been developed here but provide critical information about photosynthetic function. As mentioned earlier, our understanding of leaf bidirectional properties is still in its infancy.

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