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Wheat leaf bidirectional reflectance measurements: Description and quantification of the volume, specular and hot-spot scattering features

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ABSTRACT

This study focuses on the directionality of wheat leaf reflectance as a function of leaf surface characteristics. Wheat leaf BRF measurements were completed under 45° zenith illumination angle in three visible broad spectral bands with a conoscope that provides very high angular resolution data over a large portion of the whole hemisphere, including around the illumination direction. The measurements show a clear anisotropy with a specular lobe in the forward scattering direction and a small but significant hotspot feature in the backward scattering direction. The BRF directional features further depend on the illumination orientation because of the leaf roughness created by longitudinal veins: the specular lobe was more pronounced when the illumination was perpendicular to the veins, while specular reflection was more spread over azimuths for longitudinal illumination. Moreover, a sharp hotspot feature was observed for transversal illumination where the apparent roughness is the largest. The scattering was tentatively decomposed into specular, hotspot and isotropic components. Results showed that the hotspot contribution to the directional hemispherical reflectance factor (DHRF) was marginal conversely to that of the specular component that ranges between 0.036 and 0.050 (absolute DHRF value). The specular component was almost the same in the three visible bands considered. The isotropic component originating from volume scattering was contributing the most to the DHRF and was depending on wavelength, ranging between 0.055 and 0.097 in absolute DHRF value. A simple model was proposed to estimate the volume scattering from the isotropic and the surface components. Consequences of these findings were drawn on the ability to estimate leaf biochemical composition independently from leaf surface scattering, as well as on the interpretation of remote sensing at the canopy level.

1. Introduction

The description of leaf optical properties, i.e. reflectance, transmittance and absorptance is important for understanding several processes intervening within the functioning of the canopy (Terashima & Saeki, 1983). Hence, it may serve a wide range of environmental, ecological and agricultural related applications. Emphasis was mainly put on the capacity to estimate the leaf biochemical composition from the spectral variation of optical properties. This was illustrated by several studies over a range of scales, from the leaf (Fourty et al., 1996; Gitelson et al., 2003; Markwell et al., 1995), high throughput phenotyping issues (Mistele & Schmidhalter, 2008), up to remote sensing applications (Fourty & Baret, 1997; Fourty et al., 1996; Jacquemoud et al., 2009). However, very little attention has been paid to leaf directional properties that may induce problems in the retrieval of leaf biochemistry at the leaf and canopy levels, as well as when exploiting the bidirectional reflectance distribution function (BRDF) to estimate canopy structural attributes such as Leaf Area Index (LAI). As a matter of fact, information on the biochemistry comes from the absorption by the constituents occurring within the leaf, whereas the anisotropy of leaf reflectance originates mainly from processes taking place at the leaf surface including specular reflection (Breece & Holmes, 1971; Grant et al., 1987), shadowing created by leaf roughness (Bousquet et al., 2005) and scattering by trichomes on leaves (Holmes & Keiller, 2002; Levizou et al., 2004). A number of solutions have been proposed to limit the variability due to leaf surface properties. They include specific measurement configurations such as using an integrating sphere under normal illumination providing directional hemispherical measurements and transmittance measurements (Fourty et al., 1996). Further, specific processing methods are proposed to be applied to the measurements (McClendon & Fukshansky, 1990; Rondeaux & Vanderbilt, 1993), exploiting the fact that most surface processes are mainly driven by surface structure and the refractive index of the surface material that varies little with wavelength in the visible and near infrared domains, leading to wavelength independent features (Saunderson,

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1942). However approximations and difficulties in the implementation of these solutions prevent getting accurate and robust estimates of leaf biochemical composition across species, cultivars and environmental conditions.

At the canopy scale, very little attention has been paid to the impact of leaf scattering phase function on canopy reflectance, leaves being generally assumed Lambertian with no differences between faces. However, Chelle (2006) used a simple BRDF (Bi-directional Reflectance Distribution Function) model to evaluate whether the Lambertian assumption was leading to accurate simulations of light absorption in the canopy. He concluded that the effect was marginal, although these results may be highly impacted by the leaf BRDF model used that was not necessarily very realistic. More recently, (Stuckens et al., 2009) demonstrated that the leaf BRDF impacted significantly canopy reflectance over citrus crops with a magnitude that depend on directions and wavelengths, showing that the architecture of the canopy plays also an important role. Nevertheless, the lack of knowledge about leaf anisotropy was already pointed out as one of the main limiting factors in our capacity to accurately describe canopy BRDF (Lewis, 2007).

Bi-directional scattering distribution function (BSDF) allows characterizing the anisotropy of both leaf reflectance (BRDF) and transmittance (BTDF) of the two faces. The early work on leaf BRDF (Howard, 1969) shows a lobe of high reflectance in the forward scattering direction, with a larger magnitude for the larger zenith illumination angles. This is interpreted as resulting from the specular reflectance that was later modeled by Torrance and Sparrow (1967) assuming the leaf surface made of facets with a given distribution of their orientation. The model was later adapted by Bousquet et al. (2005) who included mutual masking created by leaf roughness. However, some leaves showing particular BRDF features such as cereals could not be faithfully modeled using these assumptions (Combes et al., 2007). Other authors have identified a hot-spot in the backscattering direction originating from the mutual shadowing of the surface roughness features (Howard, 1969).

Most experimental studies on leaf BSDF were done using a goniometer where the illumination source and/or the sensor are rotating around the leaf sample (Combes et al., 2007; Walter-Shea et al., 1989). However, these measurements take time with consequences on leaf state mainly because of the desiccation during the experiment (Brakke et al., 1989). Further, difficulties to sample the hot-spot direction because of self-shadowing between the source and the sensor and the increased footprint for the larger view zenith angles limit the angular range. Sarto et al. (1989) proposed an imaging sphere made of a reflective hemisphere that is imaged by a fish-eye camera. This alternative leaf BSDF technique is promising since measurements should be almost instantaneous and with a high angular sampling and resolution. However, this technology developed for specific industrial applications (Rykowski, 2008) has not yet been used for leaf BSDF measurements. Other communities have been very active in developing a new BRDF measurement technique based on Fourier optics. The resulting conoscope system (2004; Ged et al., 2010; Obein et al., 2001), allows unprecedented angular sampling both in terms of range and resolution while measurements are sufficiently rapid to maintain the leaf in good conditions during data acquisition. The objective of this study is to provide a detailed description of leaf BRDF in the visible domain over wheat leaves using the conoscope system. Wheat represents the most cultivated crop and several agriculture applications focusing either on precision farming or high throughput phenotyping exploit canopy reflectance measurements for characterizing structural traits such as leaf area index or leaf attributes including chlorophyll content. The measurements achieved aimed at better understanding the main processes governing wheat leaf BRDF and quantifying their contribution to the directional hemispherical reflectance or albedo.

2. Materials and methods

The conoscope EZ-Contrast80M designed by Eldim SA (www.eldim.fr) was used in this experiment. It is based on a Fourier optic lens (Bass, 1995; Saleh & Teich, 1991) that projects the angular distribution (θ_ν, φ_ν) of the reflected radiation onto a cooled Charge Coupled Device (CCD) matrix (Fig. 1). A regulated xenon arc light source with a collimated beam (solid angle $<10^{-4}$ sr) was passing through a diaphragm with 0.33 mm diameter aperture, corresponding to the size of the light spot on the leaf. The direction of the incident beam may be manipulated both in zenith and azimuth directions. However, the zenith illumination was fixed at $\theta_s = 45°$ in this study, while the azimuth illumination was set either parallel to the leaf longitudinal direction ($\varphi_s = 0°$) or transversally ($\varphi_s = 90°$) (Fig. 2). The change between longitudinal to transversal illumination was achieved by rotating the leaf. The size of the illuminated spot on the leaf was slightly larger than the spot sampled by the Fourier optics. Radiance signal is recorded in all azimuth directions and with zenith angles up to 80° over a 400 × 400 CCD matrix. The signal is finally transformed into a 80 × 360 matrix corresponding to zenith view angles $0° \le \theta_\nu \le 80°$ and view azimuth $0° \le \varphi_\nu \le 360°$ by 1° step.

Five spectral filters mounted in front of the sensor matrix (Fig. 1) are combined to compute the *XYZ* tristimulus values (CIE 1931) used in vision related applications for which the conoscope was originally designed. Each tristimulus coordinate corresponds to the radiance measured in a broad band with a spectral sensitivity shown in Fig. 3. The XYZ coordinates correspond roughly to a Red, Green and Blue bands and we will use this last denomination along this study.

The signal corresponding to each element of the 80 × 360 matrix in a given band λ is proportional to the luminance of the target, $L(\theta_s, \varphi_s, \theta_\upsilon, \varphi_\upsilon, \lambda)$. The calibration coefficient $\alpha(\theta_s, \varphi_s)$ depends only on the illumination geometry, the conoscope being designed to provide repeatable values across the view geometries, i.e. valid for the whole 80 × 360 matrix. Further, for a given geometry, the calibration coefficient $\alpha(\theta_s, \varphi_s)$ was constant with time during the experiment since the light source and the sensor matrix were stabilized. An experience made using a light trap showed that under the illumination condition ($\theta s = 45°$) the stray light effects were found at the same level than instrumental noise or lower. According to this result, no correction of stray light was applied. A Labsphere Spectralon reference panel was used to transform the measured radiance values into bidirectional reflectance factor, $\mathrm{BRF}(\theta_s, \varphi_s, \theta_\upsilon, \varphi_\nu, \lambda)$ the main physical quantity used in this study. Several studies reported that the Spectralon panels were not perfect Lambertian surfaces (Bruegge et al., 2001; Jackson et al., 1992), in agreement with our observations (Fig. 4). The manufacturer of the Spectralon panel provides the directional hemispherical reflectance factor for nadir ($\theta_s = 0°$) illumination: $DHRF_{ref}(0°, \lambda) = 0.991$ for λ corresponding to the 3 wavebands considered. Since our illumination configuration is different ($\theta_s = 45°$) it was approximated that $DHRF_{ref}(45°, \lambda) \approx DHRF_{ref}(0°, \lambda)$, hence assuming that the absorption of the panel is about constant (and very small) up to $\theta_s = 45°$. This was later confirmed by independent measurements made with a goniometer (results not shown for the sake of brevity). In these conditions, the BRF of the leaf is computed as:

$$BRF_{leaf}(45^\circ, \varphi_s, \theta_\nu, \varphi_\nu, \lambda) = 0.991 \frac{L_{leaf}(45^\circ, \varphi_s, \theta_\nu, \varphi_\nu, \lambda)}{\frac{\sum_{\varphi\nu=0^\circ}^{360^\circ} \sum_{\theta\nu=0^\circ}^{90^\circ} L_{ref}(45^\circ, \varphi_s, \theta_\nu, \varphi_\nu, \lambda) \sin(\theta_\nu) \cos(\theta_\nu)}{\sum_{\theta\nu=0^\circ}^{90^\circ} \sin(\theta_\nu) \cos(\theta_\nu)}} \quad (1)$$

Where $L_{ref}(45°, \varphi_s, \theta_\nu, \varphi_\nu, \lambda)$ and $L_{ref}(45°, \varphi_s, \theta_\nu, \varphi_\nu, \lambda)$ are the signals measured respectively on the leaf and on the reference panel. Because of the absence of measurements above 80°, the integration over the whole range of view zenith angles in Eq. (1) was computed assuming a linear variation with θs of the term $L_{ref}(45°, \varphi_s, \theta_\nu, \varphi_\nu, \lambda)$ sin $(\theta_\nu)\cos(\theta_\nu)$ for $80° < \theta_s < 90°$, taking advantage of the properties