IMPACTS OF DIRECTIONAL REFLECTANCE ON THE RETRIEVAL AND INTERPRETATION OF SUN-INDUCED CHLOROPHYLL FLUORESCENCE

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ABSTRACT: Solar-induced chlorophyll fluorescence (ChlF) retrieval from the observed reflected radiance has attracted great interest since the ChlF is directly linked to the photosynthesis. however, ChlF estimates from the observed apparent radiance by the fraunhofer line discrimination (FLD) method are significantly affected by the directional reflectance. This study explores directional impacts on ChlF estimates by in-situ multi-angular spectral measurements. Results show that the ChlFs in both O_2-B and O_2-A absorption bands vary greatly with observing angles, and the former shows much higher sensitivity to directional reflectance than the later. Given this, a possible retrieval method using Bidirectional Reflectance Distribution Function (BRDF) models was suggested to interpret the directional effects. This study provides further insights into the characteristics of the sun-induced canopy ChlF.

1. INTRODUCTION

The chlorophyll fluorescence (ChlF) emitted by the photosynthetic apparatus, has been long considered a perfect proxy of vegetation photosynthesis (Govindjee 1995). Recently, a wide range of interest in ChlF has been extended to the Earth Observation (EO) community, since the ChlF has the potential to offer a completely new, appealing and immediate solution to non-destructively monitor plant status and function from aircraft / satellite scales (Meroni et al. 2009). Remote retrieval of sun-induced ChlF from space can provide increased insights into the inner working mechanisms of global vegetation in response to the Earth's environment. This may potentially advance the understanding of regional and global vegetation photosynthesis, carbon/water cycles, energy exchange and climate change etc. As a result, a number of scientists from world-wide institutions and organizations such as the European Space Agency (ESA) and NASA have recently concentrated on the ChlF retrievals and its applications (Meroni et al. 2009; Moreno 2006).

However, ChlF retrievals via the fraunhofer line discrimination (FLD) from the top-of-atmosphere (TOA) radiance suffer from various influencing factors, including the atmospheric scattering, sensor configurations, canopy structure, species, phenology, sun-sensor geometry, algorithms and background. These impact factors, ultimately confounding the retrieval of weak ChlF that only accounts for a very small amount of the total reflected radiation (< 5% in near infrared bands) (Damm et al. 2011), need to be assessed and separated. To date, some of the factors have been initially investigated, including the atmospheric aerosols, canopy structure and sensor characteristics (Damm et al. 2011; Fournier et al. 2012; Frankenberg et al. 2011). Among the influence factors, a critical one—the directional effect, to our knowledge, has been seldom reported, although there are several studies having recognized the viewing geometry effects on remotely sensed ChlF (Damm et al. 2011; Guanter et al. 2010; Meroni et al. 2008).

The objective of this paper is to investigate the viewing directional effects on the ChlF estimates in both O_2-A (~761 nm) and O_2-B (~688 nm) atmospheric absorption bands by in-situ multi-angular measurements, and subsequently, some feasible suggestions to eliminate the angular effects of the ChlFs will be given. In this study, we have assumed that the observed reflectance exhibits strong directional variability, whereas the emitted ChlF from chlorophyll pigment-protein complexes features no or weak viewing directional effect at a given illumination direction, which thus can be approximately regarded as isotropic radiation. Nevertheless, the remotely sensed ChlF may be polluted by the directional reflectance and thereby causes clear anisotropy.

2. METHODOLOGY

To investigate the directional effects on the remotely sensed ChlF, multi-angular canopy spectra of lawn grass were collected on a clear day by a self-developed portable BRDF measurement device, combined with an ASD FieldSpec Pro FR spectroradiometer (Analytical Spectral Devices, Inc.). The fiber optic with a 25 °field-of-view (FOV) of the ASD spectrometer was mounted on the BRDF measurement device at a height of 80 cm, resulting in a circular field with a diameter of ~35.5 cm when measured at nadir position. For each viewing direction, 5 repeated measurements in the range of 350-2500 nm with a sampling interval of 1 nm and a spectral resolution of 3 nm for 350-1000 nm and 10 nm for 1000-2500 nm were obtained. In order to minimize the variation of solar zenith angles (SZAs), 13 angular measurements in the solar principle plane from -60 °to 60 °view zenith angles (VZAs) with the increment of 10 °were accomplished within 11 minutes. A spectralon standard panel (approximately diffused reflector, ASD, Inc.) was simultaneously measured at nadir position to calibrate the radiance into the bidirectional reflectance factor (BRF). Figure 1 shows the BRF of lawn grass over the 350-2500 nm measured at VZA=0 °, where the three typical noisy spectral regions resulting from water atmospheric absorption were removed. The subwindow in figure 1 shows the ChlF filling-in effect in 761 nm.

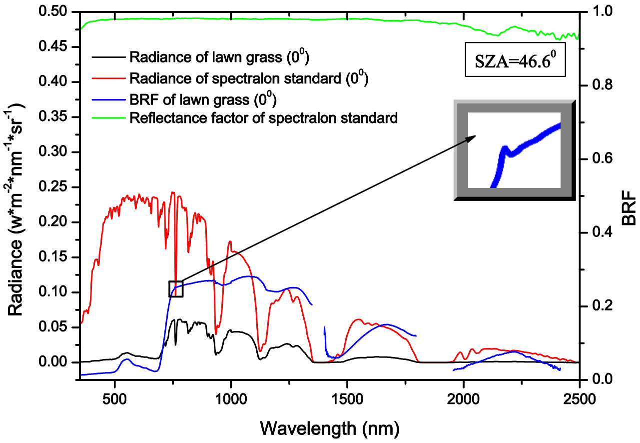

Fig. 1. Lawn grass BRF (blue) at VZA=0 °calculated by the radiances of grass (black) and spectralon panel (red).

As most previous studies pointed out, the absolute ChlF intensity in red and far-red wavelengths can be successfully quantified through the fraunhofer line discrimination (FLD) method (Meroni et al. 2009). The rationale is that the two ChlF peaks happen to be located in the vicinity of the telluric O_2-B (~688 nm) and O_2-A (~761 nm) absorption bands, where the incident irradiances are almost attenuated before entering the vegetation, thereby resulting in two dark lines. Refer to figure 2 (the basic principle of the FLD method), by comparing the filling-in depth of radiances reflected by vegetation at the same bands, the fluorescence emission can be derived as equation (1), where the solar irradiances in and out of O_2 bands are replaced by the simultaneously measured radiances (L_{r_in} and L_{r_out}) of the spectralon standard (see figure 2 (a)) with corresponding calibration factors of f_{r_in} and f_{r_out}. Note L_{v_in} and L_{v_out} in equation (1) are corresponding radiances of vegetation (see figure 2 (b)).

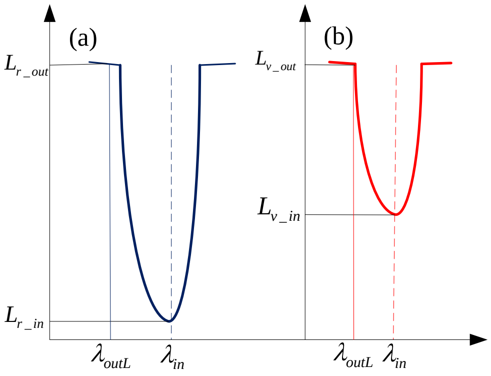

Fig. 2. The FLD principle

$$ChlF = \frac{\left(\frac{L_{r\_out}}{f_{r\_out}}\right) \times L_{v\_in} - L_{v\_out} \times \left(\frac{L_{r\_in}}{f_{r\_in}}\right)}{\left(\frac{L_{r\_out}}{f_{r\_out}}\right) - \left(\frac{L_{r\_in}}{f_{r\_in}}\right)} \qquad (1)$$

3. RESULTS AND DISCUSSION

To illustrate the reflectance anisotropy of lawn grass, BRFs of 9 bands covering the visible-infrared spectral range were plotted against VZAs in Figure 3(a). For all the selected bands, BRFs increase with increasing VZAs, exhibiting the “bowl shape” variability. In order for deeper insight into the directional characteristics, a normalized difference reflectance factor (NDRF) was defined here using the BRF as

$$NDRF(\theta_v, \lambda) = \frac{BRF^{\lambda}_{\theta_v = i} - BRF^{\lambda}_{\theta_v = 0}}{BRF^{\lambda}_{\theta_v = i} + BRF^{\lambda}_{\theta_v = 0}}, \text{ where } \; i \in [-60, 60] \qquad (2)$$

Using equation (2), NDRFs of the selected bands were computed (Figure 3(b)). Compared with Figure 3(a), the reflectance anisotropy is much more pronounced in Figure 3(b), displaying very strong directional sensitivities.

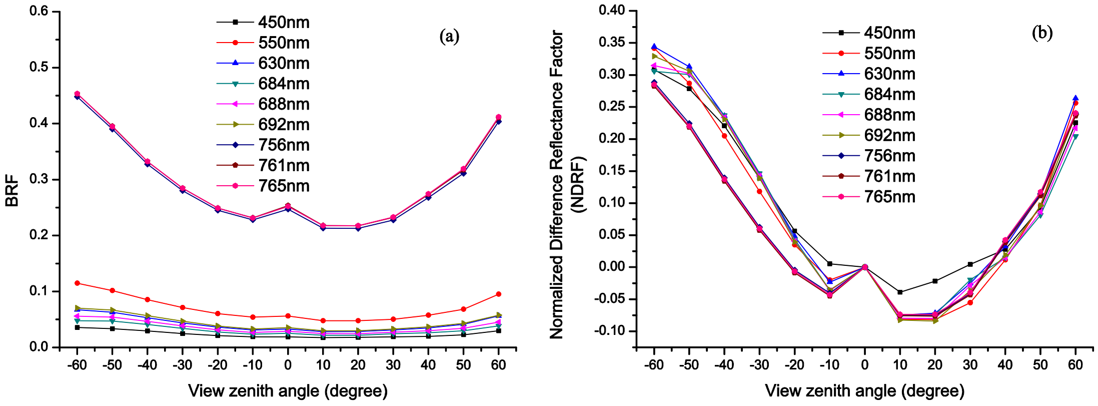

Fig. 3. Directional reflectance characteristics of lawn grass for 9 selected bands: (a) BRF, (b) NDRF.

Generally, the observed reflectance can be divided into three components, namely the isotropic scattering, geometric scattering and volumetric scattering. The significant “bowl shape” NDRFs in Figure 3(b) may be ultimately attributed to the last two components, whereas the isotropic component normally has identical contribution for all BRF view directions. Apart from the three recognized reflection portions, an easily ignored (very weak) but rather important emission signal—sun-induced ChlF is also superimposed into the observed reflectance by remote sensors. Figure 1 clearly indicates the ChlF filling-in effect in O_2-A band, where a sudden reflectance rise occurs. Using equation (1), the two solar-excited ChlF peaks at 688 nm and 761 nm (their corresponding reference bands are 684 nm and 756 nm respectively) can be further quantified as shown in Figure 4.

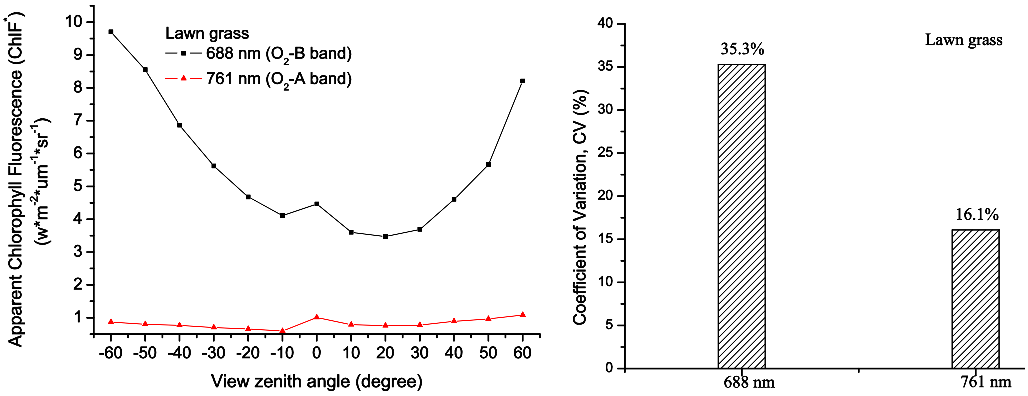

Fig. 4. Apparent ChlFs in 688 nm and 761 nm: Left, apparent ChlFs; Right, CVs of the ChlFs

Referring to Figure 4, similar to the BRF, the retrieved ChlF also suffers heavily from directional variability. The degree of ChlF variation with VZAs was then measured by the coefficient of variation (CV, the ratio of standard deviation and mean value). For O_2-B band, the ChlF varies greatly with VZAs with the CV of 35.3%, while a relative low CV of 16.3% for O_2-A band is achieved. The less angular sensitivity of the derived ChlF in O_2-A band may be interpreted by the higher transmittance property in near infrared bands for grass canopy, which produces high multiple scattering and thereby degrades the reflectance anisotropy (Gao et al. 2003). Therefore, more cares should be taken with directional reflectance effects when deriving the sun-induced ChlF in O_2-B band by the FLD.

Given that the emitted ChlF can be reasonably approximated as the isotropic emission (Gilerson et al. 2006; Joiner et al. 2011), the variability of ChlF is thought to be possibly from the directional reflectance. Another interesting finding in Figure 4 is that the ChlF shape versus VZAs at 688 nm coincides fairly well with the corresponding BRF and NDRF curves in Figure 3. From this view, we could further deduce that the angular variations in the estimated ChlF are largely due to the observed directional reflectance. In addition, the inappropriate assumption of isotropic surface reflectance for the FLD method to a large extent contributes to the ChlF variations (Damm et al. 2011).

The observed ChlFs from the apparent reflected radiances may be contaminated by directional reflectance and hence show directional variations against the view angles. The existence of directional nature of the observed ChlF from remote sensing data may reduce the link to the vegetation physiology. As discussed above, in order to eliminate the effect of directional reflectance on the ChlF retrieval, a three-term kernel driven BRF model as shown in equation (3) could be suggested to obtain the isotropic scattering radiance using multi-angular observations. In this way, the directional issue of remotely sensed ChlFs may be effectively tackled in principle due to without the contamination of directional reflectance.

$$BRF(\theta_s,\theta_v,\Delta\phi,\lambda)=f_{iso}(\lambda)+f_{geo}(\lambda)\cdot K_{geo}(\theta_s,\theta_v,\Delta\phi,{}^{h}\!/_{b},{}^{b}\!/_{r})+f_{vol}(\lambda)\cdot K_{vol}(\theta_s,\theta_v,\Delta\phi) \qquad (3)$$

Here, f_{iso}, f_{geo}, f_{vol} are three unknown kernel weights for the isotropic, geometric and volumetric scattering components at wavelength λ respectively. K_{geo} and K_{vol} are the geometric and volumetric kernels. Both are functions of the SZA (θ_s), VZA (θ_v) and relative VAA ($\Delta\phi$). The K_{geo} is additionally controlled by the canopy relative height ($^{h}/_{b}$) and the canopy relative shape ($^{b}/_{r}$), for detailed information regarding the BRDF models, please refer to Li *et al*. (2001). Furthermore, due to exempting from directional effects, the isotropic radiance would be more consistent with the implied assumption of lambertian surface reflection in the FLD method.

4. CONCLUSIONS AND PROSPECTS

Using ground-based multi-angular spectral data of lawn grass, the directional reflectance influences on the retrievals of sun-induced ChlF in O_2-A (~761 nm) and O_2-B (~688 nm) bands were investigated. We demonstrate that the ChlF directly derived from multi-angular observations by the FLD method is the apparent ChlF that exhibits significant directional variability. The CVs over the view angles are 35.3% in 688 nm and 16.3% in 761 nm respectively. The possible reasons for this are explained by both the directional nature of reflectance and the implied assumption of lambertian surface reflectance for the widely used FLD method. Obviously, the neglect of directional reflectance effects can result in substantial errors in ChlF estimates, and then may greatly decrease the direct link between the sun-induced ChlF and vegetation photosynthesis. From this view, a possible retrieval strategy using kernel-driven BRDF models was suggested to address the directional issue. In our future study, the proposed method should be validated using various datasets from ground, airborne to spaceborne platforms.

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