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New approaches in multi-angular proximal sensing of vegetation: Accounting for spatial heterogeneity and diffuse radiation in directional reflectance distribution models

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ABSTRACT

The development of tower-mounted automated multi-angular hyperspectral systems has brought new opportunities and challenges for the characterization of the Bidirectional Reflectance Distribution Function (BRDF) on a continuous basis. This study describes the deployment of one of these systems in a Mediterranean savanna ecosystem (AMSPEC-MED), and proposes new approaches for modeling of directional effects. In this study, a Hemispherical-Directional Reflectance Distribution Function (HDRDF) was introduced in order to quantify the effect of diffuse radiation on the estimation of BRDF. The HDRDFs of the two covers of the ecosystem - trees and grasses - were un-mixed using a 3-Dimensional (3-D) model of the observed scene. Up-scaling HDRDF estimates to MODIS BRDF product ($r^2 \in [0.74, 0.86]$) and down-scaling to hand held spectral measurements ($r^2 = 0.88$) achieved a reasonable accuracy (RMSE $\in [1.81, 3.14]$). Despite the uncertainties in the estimation of diffuse irradiance and the 3-D representation of the scene, HDRDF un-mixing demonstrates the potential of automated multi-angular proximal sensing to study vegetation properties in heterogeneous ecosystems and the correction of directional effects of different sources.

1. Introduction

Highly variable in space and time, terrestrial biospheric carbon dioxide fluxes are about five-fold the annual anthropogenic emissions (Gamon et al., 2010). A better understanding of these fluxes is therefore required to better predict climate carbon feedbacks. Different tools can be used to monitor such fluxes and understand their controls (Gamon et al., 2006b). Eddy Covariance (EC) systems continuously register ecosystem carbon exchanges within their area of influence measurement (footprint) (Baldocchi, 2003). Complementarily, satellite remote sensing provides spatial information about vegetation distribution, phenology and physiology in a spatially explicit fashion; but temporarily discrete, as observation are available only during sensor overpasses (Hilker et al., 2009b). A strategy to overcome this spatio-temporal mismatch is the deployment of optical sensors that operate at the EC scale (Gamon et al., 2006b). Due to its simplicity and reduced cost, broadband mono and multi-spectral sensors were widely deployed in EC towers (Balzarolo et al., 2011). However, over the last decade, the spectroradiometers linked to EC towers have become more commonplace (Balzarolo et al., 2011; Porcar-Castell et al., 2015). Hyperspectral sensors allow detecting narrow spectral features related to vegetation physiology (Gamon et al., 1992; Meroni et al., 2009), provide overdetermined data for model inversion (Goetz, 2009), and allow mimicking sensors with coarser spectral resolution (Porcar-Castell et al., 2015).

One of the first automated hyperspectral systems developed was set up on a robotic tram carrying a dual-beam spectrometer (Gamon et al., 2006a). It acquired Hemispherical-Conical Reflectance Factors (HCRF) at temporal and spatial scales comparable to those of the EC tower (see Nicodemus et al. (1977)). Such scale matching allowed the analysis of the relationships between optical signals and vegetation physiology (Claudio et al., 2006; Gamon et al., 2013; Sims et al., 2006), and the upscaling of water and carbon fluxes (Cheng et al., 2006; Fuentes et

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al., 2006; Stow et al., 2004). Most current systems are fixed on towers operate in the visible and near infrared (Balzarolo et al., 2011; Porcar-Castell et al., 2015), short wave infrared (Huber et al., 2014; Sakowska et al., 2015); or sun induced fluorescence bands (Cogliati et al., 2015; Daumard et al., 2010; Drolet et al., 2014; Meroni et al., 2011; Middleton et al., 2013; Rascher et al., 2009).

One issue with mono-angular instrumentation is the mixing of directional effects with information about physiology and phenology. To overcome this limitation systems like the Automated Multi-angular Spectroradiometer (AMSPEC) (Hilker et al., 2007), allow the acquisition of multi-angular measurements through pan-tilt systems or rotating mirrors (Hilker et al., 2007, 2010b; Huber et al., 2014; Leuning et al., 2006; Tortini et al., 2015), thereby disentangling directional, phenological and/or physiological changes in the optical signals (Hilker et al., 2008a; Huber et al., 2014; Leuning et al., 2006). Thus far, AMSPEC-like systems have mainly operated in homogeneous ecosystems (Hilker et al., 2008a, 2010a) or in heterogeneous stands where different covers could be observed separately (Hilker et al., 2009a; Huber et al., 2014).

Directional effects are especially strong in automated sensors, since these face large ranges of illumination angles and sky conditions. Therefore, measured reflectance quantities vary according to sun-view geometry and the diffuse component of the down-welling flux (Hilker et al., 2008a; Sakowska et al., 2015; Sandmeier and Itten, 1999); the last can be expressed as the diffuse-to-global radiation ratio (δ_{dif}). Directional effects are usually addressed via BRDF modeling, based on multi-angular observations of the same surface from different angles and platforms (Burkart et al., 2015; Colgan et al., 2012; Deering and Leone, 1986; Sandmeier and Itten, 1999; Schaaf et al., 2002). On the contrary, tower mounted AMSPEC-like systems observe different patches of the surrounding canopy varying the observation angle from a fixed position. Both approaches are comparable if can be assumed that AMSPEC-like systems observe homogeneous vegetation covers (Hilker et al., 2008a, 2010a), or that their observations can be classified in different homogeneous categories (Hilker et al., 2009a). Moreover, these works used sky conditions to classify (Hilker et al., 2008a) or filter data (Hilker et al., 2009a, 2010a) prior to model BRDF. Therefore, issues related to subpixel and between pixels heterogeneity, as well as the effect of diffuse radiation on BRDF are not yet fully solved.

This work aims to enhance the current tower-based BRDF modeling approaches tackling the problems related with spatial heterogeneity and the effects of diffuse radiation. To do so, we demonstrate the applicability of a tower mounted multi-angular hyperspectral system (AMSPEC-MED) in spatially diverse environments, such as tree-grass Mediterranean savannas. Spatial heterogeneity is overcome by unmixing the directional reflectance distribution functions of the different vegetation covers; whereas diffuse radiation is included in the Hemispherical-Directional Reflectance Distribution Function (HDRDF). Both approaches are tested using AMSPEC-MED data and results are compared to MODIS and hand held spectral measurements.

2. Methods

2.1. Study site

The research area is a Mediterranean tree-grass ecosystem, also known as "dehesa", located in Las Majadas del Tietar, Cáceres, Spain (39° 56′ 29″N, 5° 46′ 24″W) at 259 m above sea level. The site is part of the FLUXNET research network (http://fluxnet.ornl.gov/site/440, last accessed July 19th, 2016). Climate is Continental Mediterranean; hot and dry summers reach over 40 °C, far above the 16.7 °C annual average, and include only 6% of the annual 572 mm rainfall (Casals et al., 2009). There are two different vegetation layers. Annual grasses are diverse; they peak in Spring, senesce by the beginning of the Summer and recover moderately with Autumn rains, before going dormant in Winter. Since vegetation is grazed, it rarely grows taller than 30 cm. Scattered Holm oak trees (*Quercus ilex* subsp. *ballota* L.) cover 20% of the ground. The mean distance between them is 18.8 m ($\sigma = 5.0$ m), mean oak height is 7.9 m ($\sigma = 0.9$ m), mean crown horizontal radius is 4.18 m ($\sigma = 0.9$ m) and mean vertical radius is 2.7 m ($\sigma = 0.5$ m) (this article).

2.2. The AMSPEC-MED system

Operational in Las Majadas site since 1st August 2013, the AMSPEC-MED (Fig. 1) is an adaptation of the AMSPEC-II (Hilker et al., 2010b). Likewise, AMSPEC-MED integrates a Unispec DC spectrometer (SN 2038, PP Systems, Amesbury, MA, USA), a dual-channel system presenting 256 spectral bands with an interval sampling of 3.3 nm and Full Width Half Maximum (FWHM) < 10 nm. Channel 1 is a 6 m optical fiber and a cosine diffuser (UNI686-6 + UNI435, PP Systems) which samples the down-welling radiant flux. Channel 2 consists of a 6 m optical fiber (UNI686-6, PP Systems) plus a 1 m extension (HPCS600IRT-1m, LEONI Fiber Optics GmbH, Berlin, Germany) linked by a SMA-905/SMA-905 connector (LEONI). The spectrometer is kept in an insulated box, cooled by two fans.

The system is deployed on a 13 m tower and feed by solar panels, which provide limited power supply. Different observation angles are driven by a weatherized PTU D46- 17.70W (Directed Perception, Burlingame, CA, USA). The PTU is mounted on a horizontal arm 40 cm away from the tower and 12 m above ground; it holds the channel 2 optical fiber and a NetCam SC 5MP. The cosine diffuser is located on top of the tower, so that no other elements cover the sky hemisphere.

AMSPEC-MED is controlled by the fitPC2i computer (CompuLab Ltd., Yokneam Elite, Israel) with a modified version of the code developed in Matlab® (Matworks, Natick, MA, USA) by Hilker et al. (2010b). The system operates when sun elevation is >20° in cycles of 30 min. Like AMSPEC-II (Hilker et al., 2010b) each cycle starts with a "solar" sequence of measurements mimicking sun elevation angle at different azimuth directions. Next, the "regular" sequence follows and the PTU scans in the azimuthal direction between 20° and 330° at 10° intervals

Fig. 1. AMSPEC-MED system deployed in Majadas del Tiétar, Cáceres, Spain.