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Impact of varying irradiance on vegetation indices and chlorophyll fluorescence derived from spectroscopy data

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ABSTRACT

Imaging spectroscopy (IS) provides an efficient tool to assess vegetation status and functioning at ecologically relevant scales. Reliable extraction of vegetation information from spatial and spectral high resolution spectroscopy data requires accurate retrieval schemes to account for the complex radiative transfer in the coupled vegetation-atmosphere system. Particularly the coupling of the atmosphere and vegetation considering combined effects of anisotropy, absorption and scattering typically relies on many assumptions, rendering estimates of direct (E^{dir}) and diffuse (E^{dif}) surface irradiance error prone. This impacts the reliability of retrieved vegetation properties. In this study we discuss and quantify the retrieval sensitivity of vegetation information using high resolution IS data to inaccurate assumptions of direct and diffuse surface irradiance. We use observations and simulations and focus on the two vegetation indices normalized difference vegetation index (NDVI) and the photochemical reflectance index (PRI), and on sun-induced chlorophyll fluorescence (Fs). Our results indicate that, even if the irradiance field (E) is exactly known, reflectance based vegetation indices show an inherent variation of 9% (NDVI) and 12% (PRI) respectively. These variations are caused by complex interactions of surface irradiance and reflectance anisotropy. The emitted Fs signal was found to be almost unaffected by those variations, if the retrieval considers surface anisotropy. Further, estimation of vegetation properties is subject to large uncertainties if instantaneous E fields are unknown. In that case, they range up to 13% for the NDVI, up to 32% for the PRI, and up to 58% for Fs. We conclude that retrieval sensitivities of vegetation indices and Fs to illumination effects must be carefully considered in data interpretation and suggest using coupled surface-atmosphere models to exploit the full information content of IS data.

1. Introduction

Our ability to understand and monitor energy and gas exchanges in the coupled atmosphere–biosphere system critically depends on information about dynamic vegetation processes (e.g., photosynthesis, transpiration) and their response to changing environmental conditions (Baldocchi et al., 2001; Sellers et al., 1997; Woodward & Lomas, 2004). Dynamic plant adaptation causes a spatio-temporal diversity of plant biochemistry, physiology, and structure along gradients of critical growth limiting factors (i.e., light, temperature, water) (Long, Humphries, & Falkowski, 1994; Nemani et al., 2003; Running et al., 2004), determining functional vegetation processes to be dependent on environmental conditions. Such diversity appears at various spatial scales but also in plant canopies along a vertical gradient of light interception, determining a vertical variation of plant functioning and structure (Damm et al., 2010; Ellsworth & Reich, 1993; Legner, Fleck, & Leuschner, 2014; Simpraga et al., 2013).

Physiological and structural differences between shaded and sunlit canopy elements (Gamon & Berry, 2012; Middleton et al., 2009) complicate the characterization of vegetation canopies and related functional responses to environmental changes. It was shown that representing a vegetation canopy as a big, fully illuminated leaf overestimates photosynthetic rates, while a separate treatment of sunlit and shaded canopy components significantly improves the modeling of vegetation photosynthesis (Alton, Ellis, Los, & North, 2007a; Alton, North, & Los, 2007b; dePury & Farquhar, 1997). Different physiological behavior of shaded and sunlit canopies can be also interpreted as a unique feature to obtain relevant canopy information such as canopy light use efficiency (Middleton et al., 2009). Recent studies already demonstrate the added value of a combined analysis of differently illuminated canopy parts to monitor functional vegetation responses (Hall et al., 2008; Hall, Hilker, & Coops, 2012; Hilker, Gitelson, Coops, Hall, & Black, 2011) or to disentangle various causes of plant stress (Gamon & Berry, 2012).

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Imaging spectroscopy (IS) provides an efficient tool to assess vegetation properties in-situ, (i.e., using field spectroscopy) and to measure vegetation properties at ecologically relevant scales using airborne or satellite observations. In particular, airborne imaging spectrometers measure surface leaving radiances at high spatial and spectral resolution and provide an increased sensitivity to subtle surface properties, e.g., related to physiological differences of shaded and sunlit canopy elements. However, the measurement and analysis of vegetation surfaces require attention, in particular if high resolution data are used. Increasing spatial resolution increases the apparent heterogeneity of vegetation surfaces in terms of e.g., reflectance anisotropy or mutual shadowing, and hence, the complexities of the underlying radiative transfer (RT). Indeed, various studies addressing vegetation canopies with high resolution data report a significant sensitivity of measurements and retrieved vegetation variables to surface illumination effects (Malenovsky et al., 2013; Zarco-Tejada, Morales, Testi, & Villalobos, 2013). This illumination sensitivity is basically related to assumptions of actual surface irradiance (E) represented as terms of direct (E^{dir}) and diffuse (E^{dif}) irradiance, in combination with effects of reflectance anisotropy (Gastellu-Etchegorry et al., 1999; Pinty et al., 2005; Strub, Schaepman, Knyazikhin, & Itten, 2003).

The critical impact of changing E fields on radiance data and subsequently retrieved reflectances and vegetation variables was already discussed and identified years ago (Adler-Golden, Matthew, Anderson, Felde, & Gardner, 2002; Gastellu-Etchegorry et al., 1999; Schaepman-Strub, Schaepman, Painter, Dangel, & Martonchik, 2006). The spectral shape and the intensity of both E components differ in response to their individual path length, which is a function of atmospheric absorption and scattering processes. E^{dif} contains a proportionally higher radiation fraction at shorter wavelengths (i.e., the blue spectral region) compared to E^{dir} due to the increasing intensity of multiple atmospheric scattering with the inverse of wavelength, and the Rayleigh scattering which even varies as the fourth power of inverse wavelength. Further, at higher solar elevation angles, the fractional absorption in strong atmospheric absorption lines is higher for E^{dif} compared to E^{dir}, because multiple scattering increases the atmospheric photon path lengths, and therefore increases the probability of photons in the diffuse field to be absorbed. These differences in the optical properties of the incoming radiation at the surface in combination with the reflectance anisotropy of surfaces cause complex sensitivities for surface leaving radiances. If surface E is not accurately characterized, retrieved reflectance data and subsequently derived vegetation variables include significant uncertainties.

Top-of-canopy (ToC) approaches that rely on surface reflectance data to extract information from imaging spectroscopy (IS) data, typically sequentially apply atmospheric correction and biogeophysical variable retrievals. This retrieval scheme is affected by intrinsic uncertainties as atmospheric compensation approaches include various simplifying assumptions (e.g., Lambertian surface reflectance) that hinder the exact description of the RT of the coupled vegetation-atmosphere system (Laurent, Verhoef, Clevers, & Schaepman, 2011a; Laurent, Verhoef, Damm, Schaepman, & Clevers, 2013). Further, due to lack of adequate auxiliary data (i.e., accurate digital object models (DOM) in high resolution) or atmospheric parameters (i.e., actual aerosol phase functions), pixel-wise fractions of E^{dir} and E^{dif} are approximated using the sun-observer geometry or topography information based on coarse digital elevation models (DEM) only.

This study assumes that higher information content can be extracted for physiological and biochemical vegetation properties from IS when analyzing entire canopies, stratified for their shaded and sunlit parts. We therefore i) demonstrate and discuss the sensitivity of canopy reflectance, vegetation indices and Fs derived from spatial and spectral high resolution IS data in response to varying irradiances and ii) evaluate retrieval errors caused by inaccurate estimates of actual E fields including fractional amounts of E^{dir} and E^{dif}. We deliberately focus our quantitative analysis on using ToC reflectance (R^{ToC}) and radiance (L^{ToC}) data of simple vegetation canopies with volume scattering being the dominant scattering mechanism (e.g., crops, meadows) and experimentally vary through simulations the fractional portions of E^{dir} and E^{dif}. A full quantification of the impact of changing E fields on the retrieval of vegetation information in complex 3D canopies (e.g., forests) dominated by all scattering effects (geometric-optical, volumetric and isotropic) would require more specific and comprehensive analysis and a detailed assessment of the underlying RT. After summarizing the RT of coupled vegetation–atmosphere systems, we i) demonstrate the appearance of varying irradiance in airborne spectroscopy data, ii) quantify the impact of uncertain estimates of E^{dir} and E^{dif} on radiance and reflectance spectra from homogeneous vegetation canopies, and iii) quantify the respective impact on vegetation indices and Fs considering various canopy structural parameters, atmospheric states, and observation geometries. We use simulated and observed data and focus on the normalized difference vegetation index (NDVI), the photochemical reflectance index (PRI), and sun-induced chlorophyll fluorescence (Fs). Results of this study contribute to the total error budget of IS-based approaches to measure plant functional properties from simple structured vegetation canopies. Observed sensitivities indicate the need to further develop IS data pre-processing algorithms and retrieval schemes for vegetation information and suggest using coupled atmosphere-surface models to exploit the large information content of IS data.

2. Fundamental basis

The analytical four-stream theory (Verhoef, 1985; Verhoef & Bach, 2007) provides a reasonably accurate but still relatively simple framework to describe the RT of coupled atmosphere–surface systems. Four spectral flux types are distinguished, which are i) the downward direct solar flux, ii) the diffuse downward flux, iii) the diffuse upward flux (E^+), and iv) the upward spectral radiance in the direction of the observer. According to this theory, E incident on a given surface basically consists of two fluxes, the direct flux (E^{dir}), which are photons directly transmitted between top-of-atmosphere and the surface, and the diffuse sky radiation (E^{dif}), which is a combination of the diffuse downward flux and the back-reflected diffuse upward flux and represents photons scattered more than once due to interactions with atmospheric or surface elements.

E^{dir} of a homogeneous surface without topography effects can be approximated as a function of the extraterrestrial solar irradiance (E^0), direct transmittance of the atmosphere for sunlight (τ_{ss}), and the cosine of the illumination zenith angle θ_{il}, with

$$E^{dir} = \tau_{ss} E^0 \cos\theta_{il} \tag{1}$$

The cosine of the illumination zenith is defined by

$$\cos\theta_{il} = \cos\theta_n \cos\theta_s + \sin\theta_n \sin\theta_s \cos(\varphi_n - \varphi_s) \tag{2}$$

where θ_s and φ_s are the zenith and azimuth angles of the sun rays and θ_n and φ_n are the zenith and azimuth angles of the surface normal vector.

Given a specific sun position and status of the atmosphere, E^{dif} of a flat homogeneous surface is a function of atmospheric absorption and scattering, typically approximated with the diffuse transmittance of the atmosphere for sunlight (τ_{sd}), and a component accounting for the multiple reflection of E between the target and its surroundings and the atmosphere, the spherical albedo of the atmosphere ρ_{dd}, and can be expressed as

$$E^{dif} = \tau_{sd} E^0 \cos\theta_{il} + \rho_{dd} E^+ \tag{3}$$

E^+ can be approximated with

$$E^+ = \overline{r_{sd}} E^{dir} + \overline{r_{dd}} E^{dif} \tag{4}$$