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Diffuse sky radiation influences the relationship between canopy PRI and shadow fraction

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ABSTRACT

The Photochemical Reflectance Index (PRI) of green leaves is an indicator of photosynthetic downregulation: when the photosynthetic apparatus is close to the saturation limit, PRI becomes dependent on light conditions. Therefore, by measuring the PRI of leaves under different local irradiance conditions, it should be possible to determine the saturation level of the leaves and obtain information on the light use efficiency (LUE) of a vegetation canopy. The dependence of PRI on the ratio of sunlit to shaded foliage (quantified by the canopy shadow fraction) in the field of view of an instrument has been used to remotely measure canopy LUE on clear days. However, besides photosynthetic downregulation, the dependence of canopy PRI on shadow fraction is affected by the blue sky radiation caused by scattering in the atmosphere. To quantify this effect on remotely sensed PRI, we present the underlying definitions relating leaf and canopy PRI and perform the required calculations for typical midsummer conditions in Central Finland. We demonstrate that the effect of blue sky radiation on the variation of PRI with canopy shadow fraction is similar in shape and magnitude to that of LUE variations reported in literature.

1. Introduction

Under natural irradiation conditions, the spectral properties of leaves are dominated by diffuse scattering of incident light by leaf inner structures (Grant, 1987). Within-leaf concentrations of biological pigments (e.g., chlorophyll or carotenoids) thus strongly influence leaf spectral scattering by absorbing radiation with specific wavelengths. The spectrally selective absorption can be used to determine pigment concentrations rapidly and nondestructively using optical measurements.

Gamon et al. (1992) demonstrated that leaf optical properties at 531 nm track the epoxidation state of xanthophyll cycle pigments. The three pigments (zeaxanthin, antheraxanthin and violaxanthin) involved in the cycle have different absorption coefficients at this particular wavelength in the green part of the optical spectrum. The xanthophyll pigment interconversion cycle is activated by excess light and it has an important role in leaf photoprotection. Under saturating irradiance conditions, violaxanthin is converted to zeaxanthin creating a pathway for dissipating excess light energy as heat (Demmig-Adams and Adams, 2006). Therefore, optical measurements can be used to track the photosynthetic downregulation of a leaf, and offer a fast and non-destructive way to measure its photosynthetic status, potentially from a large distance.

The influence of the xanthophyll cycle on the optical properties of the leaves is commonly quantified using the Photochemical Reflectance Index (Gamon et al., 1992) defined as

$$\mathrm{PRI} = \frac{\omega(531) - \omega(570)}{\omega(531) + \omega(570)}, \quad (1)$$

where $\omega(\lambda)$ is the spectral albedo of a canopy element (leaf, needle) at the wavelength λ (in nanometers), i.e., the fraction of radiation reflected or transmitted by the element (Knyazikhin et al., 2011, 2013). Optical properties at 570 nm are used for reference in Eq. (1): at this wavelength, $\omega(\lambda)$ is not affected by pigment interconversions.

The PRI defined by Eq. (1) for an individual leaf is directly related to its photosynthetic efficiency ε defined as the ratio of photochemically harvested CO_2 to absorbed photosynthetically

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active radiation. Unfortunately, the leaf-level relationships are masked by other biophysical variables in the reflectance signal of a vegetation canopy. Stand-level light use efficiency (LUE) cannot be inferred from traditional, mono-angle remote PRI observations (Hilker et al., 2013). However, the variation in leaf PRI with canopy location (sun or shade) makes it possible to infer canopy LUE from the derivative of PRI with respect to the shadow fraction α_S (Hilker et al., 2010, 2011a). Under normal mid-day clear-sky irradiance conditions, sun-exposed leaves experience saturating light conditions. Their PRI values become different from those of shaded leaves making canopy PRI a function of the fraction of shadowed foliage in the instantaneous field-of-view (IFOV) of the spectroradiometer. This was demonstrated both theoretically and empirically by Hall et al. (2011) using multiangular optical measurements from a flux tower and a remote sensing satellite.

All the theoretical calculations cited above are based on a direct comparison of PRI measurements made on clear days under different view angles ignoring scattering in the atmosphere and multiple scattering in the vegetation canopy. Indeed, it is rather trivial that in case photons undergo a single scattering event between the source (sun) and the sensor, a normalized difference reflectance index (such as PRI) does not change with the viewing geometry unless the reflectance value in one of its bands changes. In the visible part of the spectrum including the wavelengths used in PRI, multiple scattering inside the vegetation canopy can be ignored to a reasonable accuracy. However, this may not be the case for the spectrally selective scattering in the atmosphere before the photons enter the canopy, especially under clear skies. Thus far, the effects of the atmosphere on measured canopy PRI have been investigated only to a limited extent. Hall et al. (2011) demonstrated that the influence of atmospheric scattering and absorption on PRI can be ignored for canopy-reflected radiation. The extent to which scattering in the cloudless atmosphere – or blue sky radiation – affects the PRI – α_S relationship has not been investigated yet.

The aim of our investigation is to present an analysis and model-based calculations of the non-biochemical factors affecting retrieval of canopy LUE from multiangular measurements of PRI. In other words, to untangle the geometric and biophysical causes of the variation of PRI with view angle, we keep leaf optical properties constant with the shadow fraction. We start by specifying the physical basis for relating multiangular canopy and leaf reflectance measurements. Using data from literature, we perform a quantitative analysis of the purely geometric effects interfering with remote measurement of the leaf-level ε.

2. Theory and materials

2.1. Leaf and canopy reflectance

The reflectance factor of a forest when measured directly above its canopy is defined as the ratio of the actual radiance scattered into the IFOV of the spectroradiometer (I_F) to the theoretical value obtained when measuring a non-absorbing Lambertian (i.e., diffusely reflecting) surface under identical irradiation conditions (I_L),

$$R(\lambda) = I_F(\lambda)/I_L(\lambda). \quad (2)$$

Thus, for a direct retrieval of $R(\lambda)$, two radiation measurements have to be made. In remote sensing applications, an air-, satellite- or mast-born instrument is used to measure the radiance reflected by the object. The additional measurement of the radiance produced by the totally reflecting Lambertian surface can be taken (near-)simultaneously with the reflectance measurement (e.g., Hilker et al., 2010). Alternatively, it can be replaced by a numerical computation using the relatively stable solar irradiance spectrum and an atmospheric radiative transfer model. Further, instead of $I_L(\lambda), R(\lambda)$ may be expressed using the flux density of the radiative energy incident on the top-of-canopy surface, or the incident spectral irradiance $F(\lambda)$. As the bidirectional reflectance distribution factor of a non-absorbing Lambertian surface, $R_L \equiv \pi^{-1}$, and $I_L(\lambda) \equiv R_L F(\lambda)$, we obtain

$$R(\lambda) = \pi I_F(\lambda)/F(\lambda). \quad (3)$$

In more technical terms, the reflectance factor defined by Eq. (2) is the hemispherical-directional, or, for a sensor with a wide IFOV, hemispherical-conical reflectance factor (Schaepman-Strub et al., 2006). It is a weighted average of the theoretical reflectance factors obtained under diffuse-sky and direct solar irradiation conditions.

Similarly to Eq. (2), we obtain from the defining equation for the spectral albedo $\omega(\lambda)$ of a canopy element (leaf, shoot, needle, etc. depending the actual canopy structure)

$$\omega(\lambda) = \pi \bar{I}_F(\lambda)/\phi(\lambda), \quad (4)$$

where $\bar{I}_F(\lambda)$ is the spectral radiance originating from the element averaged over all directions and all element area, and $\phi(\lambda)$ is the average spectral irradiance incident on the total (all-sided) surface area of the element. In case of a completely closed canopy, we may ignore the contribution of understory and assume that the radiance I_F is contributed by canopy elements only. Further, if we have a remote sensing instrument with sufficiently high angular (or spatial) resolution, we may (at least theoretically) identify the individual canopy element producing the canopy reflectance signal. In this case, when we measure the canopy-leaving radiance $I_F(\lambda)$, we record the radiance scattered by an individual leaf. Next, we will make a common assumption in vegetation remote sensing: we will ignore the angular variation in leaf-scattered I_F and take $I_F = \bar{I}_F$ (e.g., assume the leaves in a broadleaf canopy to be bi-Lambertian with equal reflectance and transmittance). Now, we may solve Eqs. (3) and (4) for the common variable $I_F(\lambda)$ to arrive at

$$R(\lambda) = \omega(\lambda)\frac{\phi(\lambda)}{F(\lambda)}. \quad (5)$$

Eq. (5) explicitly connects the canopy reflectance factor $R(\lambda)$ with the optical properties of a single canopy element, $\omega(\lambda)$. Thus, it can be used to scale reflectance between the structural levels of the basic scattering element and of the whole canopy.

No actual remote sensing instrument can distinguish individual leaves. However, it is possible to choose observation directions such that the IFOV of the instrument is dominated by canopy elements with specific irradiation conditions. For example, elements observed in the backscattering (hotspot) direction are all sunlit; in the darkspot (coldspot) direction, shaded elements dominate. Therefore, in practical remote sensing applications, the $\phi(\lambda)$ in Eqs. (4) and (5) quantifies the average irradiance incident on all sides of visible canopy elements under a specific measurement geometry.

For the canopy-level PRI we can now write using Eq. (5)

$$\mathrm{PRI}_C = \frac{R(531) - R(570)}{R(531) + R(570)} = \frac{\omega(531)\frac{\phi(531)}{F(531)} - \omega(570)\frac{\phi(570)}{F(570)}}{\omega(531)\frac{\phi(531)}{F(531)} + \omega(570)\frac{\phi(570)}{F(570)}}. \quad (6)$$

We can further define the spectral distortion factor η_{PRI} as the irradiance ratio

$$\eta_{PRI} = \frac{\phi(531)F(570)}{\phi(570)F(531)} \quad (7)$$

and multiply both the numerator and denominator of the fraction on the right hand side Eq. (6) by $F(570)/\phi(570)$ to obtain a more compact result,

$$\mathrm{PRI}_C = \frac{\omega(531)\eta_{PRI} - \omega(570)}{\omega(531)\eta_{PRI} + \omega(570)}. \quad (8)$$