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Short communication

Improved estimation of light use efficiency by removal of canopy structural effect from the photochemical reflectance index (PRI)

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ABSTRACT

Remote sensing of light use efficiency (LUE) is a prerequisite for a timely evaluation of vegetation primary productivity at regional scale. With a potential in detecting the leaf de-epoxidation state of the xanthophyll cycle for heat dissipation, the photochemical reflectance index (PRI) has been demonstrated as a proxy of LUE for various plant functional types at leaf, canopy and ecosystem scales. However, increasing evidence shows that the operational application of PRI using remote sensing data is confounded by canopy structural effects, e.g., the presence of shadows in remote sensing pixels and directional effects associated with changes in illumination and viewing angles. The most important variable that controls the structural associated characteristics is the leaf area index (LAI), which is a major determinant of the absorbed photosynthetic active radiation (APAR) by a canopy. Using ground measured PRI and LUE over three growing seasons on winter wheat in China during 2005–2007, we found that canopy LAI overall explained 66% ($p < 0.001$) variance of PRI, indicating the essential of removing influences of external structural factors on PRI. Suggested by this, we defined the structural-related signal in PRI (sPRI) as a function of LAI and consequently, the residual PRI (rPRI = PRI-sPRI) would be independent on canopy structural characteristics. Our results showed that a mixed non-linear model using rPRI and variety and sampling time as fixed and random effects, respectively, had an improved accuracy in the estimation of LUE over PRI with increased coefficients of determination (R^2) for both the overall dataset and data of each year. These findings support the structural dependence of PRI and provide a solution for the removal of the structural signal. Further analysis is needed for the application of our approach in other ecosystems that have more complicate canopy structural characteristics than herbaceous monocultures.

1. Introduction

Light use efficiency (LUE) is an important determinant of the carbon (C) sequestrated by terrestrial ecosystems and it determines the efficiency with which a plant can convert absorbed photosynthetic active radiation (APAR) into biomass (Monteith, 1972). Timely assessment of LUE at regional and global scales is a main challenge for the accurate estimation of gross primary productivity (GPP) (Yuan et al., 2007; Hall et al., 2008; Beer et al., 2010; Zhang et al., 2012).

Remote sensing observations from satellite sensors offer a good way to achieve this objective, and LUE was parameterized in many ecosystem models for the estimation of GPP (Xiao et al., 2004; Gitelson et al., 2006; Wu et al., 2012). For example, the currently widely used Moderate Resolution Imaging Spectroradiometer (MODIS) GPP products adopts a biome-specific maximum LUE which is then down-regulated by environmental stresses (e.g., water, temperature) to model how much of the photosynthetic capacity is actually realized (Zhao et al., 2006; Zhao and Running, 2010). Apart from the need of meteorological data at comparable resolutions (both temporally and spatially) with remote sensing observations, a major limitation of this approach is the requirement of a pre-assigned maximum LUE, which is often not well parameterized across plant functional types (Yuan et al., 2007; Garbulsky et al., 2011). Consequently, the outputs of such models may underestimate GPP at the upper end of GPP while

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overestimate GPP at the low end for most terrestrial ecosystems (Zhang et al., 2012; Wu et al., 2014).

Alternatively, research has been tried to directly estimate LUE using remote sensing data and the photochemical reflectance index (PRI), defined as a normalized difference index using narrow band reflectance at 531 and 570 nm, is suggested to have a particularly potential in tracking LUE both from ground spectral measurements (Gamon et al., 1992; Filella et al., 2009) and satellite observations (Drolet et al., 2005, 2008; Hall et al., 2008, 2011; Goerner et al., 2009; Hilker et al., 2009). The physiological reason that underlines PRI–LUE correlation is the de-epoxidation state of the xanthophyll cycle for heat dissipation in leaves, which leads to a decrease in reflectance at 531 nm but has little effect at 570 nm (Gamon et al., 1992; Peñuelas et al., 1995). Previous reviews on PRI have shown a general consistency of the PRI–LUE correlation across various plant functional types, including crops, deciduous forests, boreal forests and Mediterranean forests (Garbulsky et al., 2011, 2013).

However, extensive studies also demonstrate several issues in the operational use of PRI as a proxy of LUE, including the presence of shadows in the remotely sensed pixels (Hilker et al., 2008, 2010; Hall et al., 2011; Cheng et al., 2012), structural effects (Hernández-Clemente et al., 2011), atmospheric scattering effects (Drolet et al., 2008) and directional effects associated with changes in illumination and viewing angles (Moreno et al., 2012). Hilker et al. (2008) shows that while isotropic PRI scattering is correlated to LUE variation, geometric scattering can be attributed to canopy level shading. Therefore, remote sensing of forest LUE from space would be achieved by measuring PRI as a function of shadow fraction using multi-angular observations (Hall et al., 2008). This has been further confirmed by the relationship between PRI derived from multi-angular observations and canopy shadow fractions (Hilker et al., 2009). A theoretical concept using a canopy reflectance model proposed by Hall et al. (2011) further validates that using PRI alone to predict canopy LUE is confounded by the shadow fraction viewed by the sensor. A recent study from Soudani et al. (2014) indicates that removing the temporal trend associated with biochemical characteristics of the canopy may improve PRI–LUE correlation. Despite the advantages of using PRI to estimate LUE reported, a universally applicable light use efficiency model based on remote sensing observation is still difficult (Goerner et al., 2011). This gives rise to one critical aspect of upscaling PRI which is the requirement of developing algorithms to account for the structural effect of vegetation.

The leaf area index (LAI), defined as half the all-sided green leaf area per unit ground area (Chen and Black, 1992) is an important canopy structure parameter due to its influence on APAR and therefore is directly related to photosynthesis. In this study, LAI is thus the primary focus for decomposing structural signal from PRI. Using field measured canopy reflectance and LUE of winter wheat over the growing seasons of 2005–2007, we propose an approach to remove structural signal from PRI and thus to investigate how it could affect the estimation of LUE. The specific objectives of our analysis are to (1) explore the contribution of canopy structural effect in canopy PRI, to (2) develop a method to remove structural signal from PRI, and (3) to analyze how this could help to model canopy LUE.

2. Materials and methods

2.1. Study sites

The study sites were located at the National Experimental Station for Precision Agriculture (<40°10.6′ N, 116°26.3′ E), Beijing, China. This experimental station has been in operation since 2001 and lies within the warm temperate zone characterized by a mean annual rainfall of 507.7 mm and a mean annual temperate of 13.8 °C (Huang et al., 2006; Wu et al., 2009). Winter wheat (*Triticum aestivum* L.), which is one of the most important crops in China, was used in this study. In the experimental station, several varieties and accessions of winter wheat were used, and each was sown and irrigated regularly within an area of around 30 m × 7.2 m (consistent among years). Twenty-six varieties and accessions of wheat were test as follows in a total of fifty-five samples distributed in three years of study: 18, 17 and 20 in 2005–2007, respectively (see Table 1 for their specific names). For each year, measurements were conducted at regular intervals on clear days over the whole growing season. Fig. 1 shows the observation dates for each year and an example of the 17 cultivars of wheat used in 2006.

2.2. Canopy reflectance and vegetation index

Canopy reflectance were measured from 380 to 2500 nm using a portable spectroradiometer (FS-FR2500, ASD, USA) with a field of view of 25° normal to the canopy at a distance of approximately 1 m from the canopy surface (no atmospheric effects). Measurements were taken by averaging 10 scans. Reflectance spectra were derived through calibration (both before and after) relative to a 99% white reference panel (Labsphere, Inc., North Sutton, New Hampshire, USA).

Two vegetation indices were used in this study, including the PRI and normalized difference vegetation index (NDVI) following these equations below (R_x represents reflectance at a given wavelength):

$$\mathrm{PRI} = \frac{(R_{531} - R_{570})}{(R_{531} + R_{570})} \tag{1}$$

$$\mathrm{NDVI} = \frac{(R_{800} - R_{670})}{(R_{800} + R_{670})} \tag{2}$$

Table 1
Descriptions of wheat varieties and accessions used in this study during 2005–2007.

Wheat types	2005 (n = 18)	2006 (n = 17)	2007 (n = 20)
6211	√	√	√
9158			√
9428	√	√	√
9507	√	√	√
95128	√	√	√
4P3	√		
CA0175			√
CA0206			√
CA16	√	√	
Chaoyou 66	√	√	√
I-93	√	√	√
Jing 411	√	√	√
Jing 9843			√
Jingdong 10			√
Jingdong 12			√
Jingdong 8	√	√	√
Jingken 49			√
Jingmai 13			√
Jingwang 10	√	√	
Laizhou 3279	√	√	√
Linkang 2	√	√	√
Lumai 21	√	√	
Nongda 3214	√	√	
Nongda 3291	√	√	√
P7	√	√	
Zhongmai16	√	√	√