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Photochemical reflectance ratio for tracking light use efficiency for sunlit leaves in two forest types

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A B S T R A C T

The estimation of maximum carboxylation rate (V_{cmax})—a critical determinant of the terrestrial carbon simulation—over space remains a challenging task. Inverting the V_{cmax} through the sunlit gross primary productivity (GPP) is a possible solution if the key parameter sunlit light use efficiency (ε_{sun}) could be acquired through remote sensing approaches. Previous studies have shown that the reflectance centered at 531 nm (R_{531}) is very sensitive to variations of ε_{sun} and the photochemical reflectance index (*PRI*, the normalized difference index using R_{531} and R_{570}) can be used as an indicator of ε_{sun} at the leaf level though little is known about the *PRI*—ε_{sun} relationship at the canopy level due to the mixing of sunlit and shaded leaves. In this study, the photochemical reflectance ratio (*PRR*, defined as the ratio between R_{531} and R_{570}) is proposed to enable the sunlit-shaded separation of the canopy reflectance observations acquired from a tower based multi-angular platform. The canopy *PRR* can be expressed as the algebraic sum of sunlit *PRR* and shaded *PRR* weighted by the visible portions of the sunlit canopy and the shaded canopy respectively. The visible portions from different angles were simulated using the 4-Scale model and the sunlit (/shaded) *PRR* was acquired through solving a set of equations describing the canopy *PRR* obtained from different angles. The relationships between the sunlit *PRR* (PRR_{sun}) and ε_{sun} were studied for a white pine stand (TP39) and a sugar maple stand (HA). At both sites, significant correlations between PRR_{sun} and ε_{sun} were obtained (R^2 = 0.57 (TP39), 0.585 (HA), $p < 0.001$), showing the ability of PRR_{sun} to track the variation of ε_{sun}. Nevertheless, differences existed in the expressions of the PRR_{sun}—ε_{sun} relationship between TP39 and HA, a general expression could not be found. Further studies have shown that introducing the normalized difference vegetation index (*NDVI*) to correct PRR_{sun} ($NDVI \times PRR_{sun}$) largely removed such differences, suggesting the potential of the *NDVI* corrected PRR_{sun} in estimating the ε_{sun} for different biomes.

1. Introduction

The maximum carboxylation rate (V_{cmax}), which controls the leaf photosynthesis rate, is a crucial parameter in terrestrial carbon estimation using process-based models. It directly affects the magnitude of the gross primary productivity (GPP) and net ecosystem productivity (NEP) (Cramer and Field, 1999; Potter, 2003; Running et al., 2004; Bonan et al., 2011). In most models based on the leaf-level Farqhuar's model (Farquhar et al., 1980), V_{cmax} is assigned uniquely for each plant function type (PFT). However, large variations of V_{cmax} within the same PFT have been widely observed (Kattge et al., 2009; Groenendijk et al., 2011a, 2011b). In order to acquire more accurate V_{cmax} for carbon cycle simulation over large areas, multiple attempts have been made to estimate V_{cmax} using remote sensing indices (Wang et al., 2008; Jin et al., 2012; Zhou et al., 2014) through the parametric regression methods (Verrelst et al., 2015). However, the relationship between V_{cmax} and *VI*s seems to vary from site to site, year to year, and even month to month. A generic relationship has not been found.

The photochemical reflectance index (PRI), constructed using the reflectance from a spectral band centered at 531 nm (R_{531}) and a reference band centered at 570 nm (R_{570}), was first proposed by Gamon et al. (1992) to track the diurnal variation of photosynthesis for sunflower leaves. Further research revealed that *PRI* is a good indicator for the inter-conversion of the xanthophyll cycle pigments which is an important mechanism to dissipate the excess energy absorbed by the plants when exposed to high-level radiation. *PRI*, which is very sensitive to the changes of light use efficiency (ε) caused by excess incoming radiation may provide an indirect way to approach the V_{cmax} estimation. For sunlit leaves exposed to excess radiation, the photosynthetic rate is not limited by the radiation level but the value of V_{cmax} (Farquhar et al., 1980).

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Theoretically, the V_{cmax} can be inverted by Farquhar (1980)'s model using the sunlit photosynthetic rate as input.

This approach turns the regional V_{cmax} simulation problem into the regional sunlit GPP simulation problem. The ability of *PRI* to track the variation of ε can thus be utilized to estimate sunlit GPP. Two major questions here are: (1) does a significant correlation between *PRI*—ε exist for sunlit leaves at the canopy level? (2) Can a generic relationship be found for different PFTs?

The close relationship between *PRI* and ε for leaves exposed to excess radiation has been demonstrated in previous studies (Gamon et al., 1997; Peñuelas et al., 1995, 1997; Ripullone et al., 2011; Garbulsky et al., 2011b). Beyond the leaf-level study, multiple attempts have been made to upscale the *PRI*—ε relationship to the canopy level. During this process, the influences of canopy structure, solar-viewer geometry and the shaded leaf fraction on *PRI* were widely recognized (Barton and North, 2001; Nichol et al., 2000; Nakaji et al., 2008; Stagakis et al., 2014; Zhang et al., 2016). The bidirectional reflectance distribution function (BRDF) of canopy *PRI* was studied through reflectance measurements obtained from a tower-based, multi-angular spectro-radiometer platform (AMSPEC) (Hilker et al., 2007; Hall et al., 2008). Hilker et al. (2008) applied a semi-empirical kernel driven model to construct the BRDF of *PRI* data acquired from AMSPEC and successfully extracted the physiological components in the canopy *PRI* signal that directly linked to the xanthophyll cycle activities for a Doulas-Fir stand.

When extending the study from stand to landscape where multiple species are involved, how the *PRI*—ε relationship performs across species is critical. In previous studies, both the canopy *PRI* and ε were mixed signals from sunlit and shaded leaves which unavoidably introduce the influence of mutual foliage shadows in the canopy into the *PRI*—ε relationship. The differences in the relationship among various observations may be caused by different shaded portions rather than the species itself (Hall et al., 2011; Hilker et al., 2010; Mõttus et al., 2015). Thus, the canopy shadowing effect has to be removed before evaluating the canopy *PRI*—ε relationship for different species.

In this study, an algorithm of performing the correlation separately for sunlit leaves and shaded leaves was proposed. This approach served two purposes: (1) to remove the influence of canopy shadows on the *PRI*—ε relationship; and (2) to obtain the *PRI*—ε relationship for sunlit leaves which can be used to estimate the sunlit GPP for V_{cmax} estimation.

To fulfill these purposes, a modified photochemical reflectance index which could be easily separated into sunlit and shaded components using the visible sunlit and shaded portions simulated by the 4-Scale BRDF model (Chen and Leblanc, 1997) was constructed. The relationship between the sunlit (shaded) signal and sunlit (shaded) ε was then evaluated for two types of forests—a white pine plantation stand and a sugar maple stand—to assess the generality of the relationship.

2. Methods

2.1. Study sites

Two sites with different plant function types were selected for this study. One is an evergreen coniferous site dominated by white pine (*Pinus strobus* L.), the other is a deciduous broadleaf forest mainly consisting of sugar maple (*Acer saccharum* Marsh.). The white pine site (TP39) is located at 42°43′N, 80°21′W near Lake Erie, beside the Turkey Point Provincial Park, Southern Ontario, Canada. It is an even-aged 75-year old stand established in 1939 and consists of 82% white pine, 11% balsam fir (*Abies balsamea* L. Mill), 4% oak (*Quercus velutina* L., *Quercus alba* L.), and 4% of red maple (*Acer rubrum* L.) and wild black cherry (*Prunus serotina* Ehrh.) (Arain and Restrepo-Coupe, 2005; Peichl and Arain, 2006). The sugar maple site (HA) is located at 45°17′N, 78°32′W within the Haliburton Forest and Wildlife Reserve, a privately owned forest in Ontario, Canada. The species composition in this stand is 93% sugar maple, 4% American beech (*Fagus grandifolia* Ehrh.), with the remaining 3% comprised of yellow birch (*Betula alleghaniensis* Britt.) and wild black cherry (*Prunus serotina* Ehrh.) (Filewod and Thomas, 2014; Geddes et al., 2014). The specifications for these two sites are summarized in Table 1.

2.2. ε separation

The ε of the canopy is calculated following its definition (Monteith, 1972; Monteith and Moss, 1977):

$$\varepsilon = \frac{GPP}{APAR} \quad (1)$$

where *GPP* is derived from the CO_2 flux observation made using the eddy covariance technique. *APAR* stands for photosynthetically active radiation (PAR) absorbed by the canopy. It's calculated based on the shortwave radiation and PAR measurements from two flux sites using Chen et al. (1999)'s method.

Similarly, the sunlit ε (ε_s) can be calculated following:

$$\varepsilon_s = \frac{GPP_s}{APAR_s} \quad (2)$$

where GPP_s and $APAR_s$ are *GPP* and APAR for sunlit leaves. $APAR_s$ is derived using the direct PAR and diffuse PAR and GPP_s is obtained through a light response curve approach (Zheng et al., inverting the maximum carboxylation rate (V_{cmax}) from the sunlit leaf photosynthesis rate derived from measured light response curves at tower flux sites, submitted to *Agricultural and Forest Meteorology*, 2016). The shaded ε (ε_{sh}) is calculated following a similar approach. Further details of these equations are given in Appendix A.

2.3. Canopy spectral observations

The canopy reflectance spectra were obtained using a modified AMSPEC II system (Hilker et al., 2010). The main instruments of this system include a pan-tilt unit featuring a tilt range of 78° and pan range of 318° (FLIR Commercial Systems, Inc. CA, USA) and a spectro-radiometer (Unispec-DC from PP Systems, Amesbury, MA, USA). Unispec-DC is a dual channel instrument containing two detectors that allow for full spectrum (310–1100 nm) measurements with a high spectral resolution (3.3 nm). One detector is connected through a fiber-optic cable to a downward looking probe with a 20° field of view (FOV) that is fixed on the pan-tilt unit to obtain the reflected radiance from the canopy and another detector is connected to the upward pointing probe equipped with a cosine receptor for sky irradiance acquisition.

Table 1
Specifications for two flux sites.

Site code	Site name	Latitude	Longitude	Vegetation type	Year	Clumping index	Peak LAI
TP39	Ontario-Turkey Point Mature Site	42.712	−80.3572	ENF	2010	0.613	8.2
HA	Ontario-Haliburton	45.283	−78.533	DBF	2011	0.98	6

ENF: evergreen needle forest, DBF: deciduous broadleaf forest.