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A MODIS-derived photochemical reflectance index to detect inter-annual variations in the photosynthetic light-use efficiency of a boreal deciduous forest

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Abstract

The relationships between ecosystem-level light use efficiency (LUE) obtained from an eddy covariance flux tower and MODIS-derived values of a scaled Photochemical Reflectance Index (sPRI) were investigated for a boreal aspen stand (*Populus tremuloides* Michx.) in Saskatchewan, Canada. Using MODIS ocean band 11 at 531 nm, we tried to detect variations in canopy reflectance related to the xanthophyll cycle. We tested several other MODIS bands as the reference band because the 570 nm reference band that had been determined to be optimum for calculating PRI in earlier studies is not available on MODIS.

While LUE varied greatly within the 2001, 2002, and 2003 growing seasons, the Normalized Difference Vegetation Index (NDVI) calculated from tower sensors remained stable. LUE had a negative exponential relationship with vapor pressure deficit and air temperature, and was at a maximum when absorbed PAR was <200 μmol m^{-2} s^{-1}. The range and magnitude of tower-based LUE values were smaller on clear days, when MODIS acquisitions were possible, than they were overall. Furthermore, the orbital parameters of the Terra and Aqua satellites restricted MODIS acquisitions to a 2.5-h period in early afternoon at our study site when LUE values were typically lower than they were earlier in the day.

Strong correlations between MODIS-sPRI and LUE were found only for backscatter reflectance scenes when band 13 (667 nm) was used as the reference band. The correlations were higher for sPRI calculated from top of atmosphere reflectances than for surface reflectances (r^2 = 0.76 and 0.53, respectively). The absolute backscatter reflectance of bands 11, 12 (551 nm), and 13 all decreased with increasing LUE. The decrease in band 13 suggests that the correlation between sPRI and LUE that we observed was caused by reductions in canopy chlorophyll content from 2001 to 2003 and/or by increased visibility of brighter non-photosynthetic material. Regional values of sPRI from 260 deciduous forest pixels in the 10,000 km^2 vicinity of the tower for two contrasting days, one in 2001 and one in 2003, were consistent with that observed for the flux tower footprint.
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1. Introduction

Between 90 and 130 Tg of carbon (C) are absorbed annually from the atmosphere by terrestrial ecosystems through the physiological process of photosynthesis (Cramer et al., 2001). This photosynthetic flux, referred to as gross primary productivity (GPP), is one of the largest components of the global C cycle (Bolin & Fung, 1992). Within the C cycle, autotrophic (R_a) and heterotrophic (R_h) respiration return C to the atmosphere. All these elements of the C cycle are sensitive to climate variability (e.g., Amiro et al., in press; Barr et al., 2004), and they tend to interact in complex ways with environmental factors such as light, nutrients, soil water, vapor pressure deficit, air temperature, and soil temperature.

As one of the largest biomes in the world, the boreal forest plays a key role in the global C cycle (Hall et al., 2004; Schlesinger, 1997). CO_2-induced climate change may be occurring at boreal latitudes (Kattenberg et al., 1996; Mitchell et al., 1990), leading to longer growing seasons or

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more intense droughts. Such climate perturbations could in turn affect the spatial and temporal characteristics of the terrestrial C cycle in boreal forests. Since the net annual C flux can be close to zero for mature forest stands (Amiro et al., in press; Goulden et al., 1997, 1998), relatively small changes in climate could influence the direction of the net annual flux. To obtain both reliable current estimates and accurate future predictions of C cycling at larger spatial scales for boreal forests, we need to make the best possible use of remote sensing inputs into ecosystem process models (Running et al., 1999; Turner et al., 2004).

Data from the satellite-borne MODerate Resolution Imaging Spectroradiometer (MODIS) are currently used in the calculation of global weekly GPP at 1-km spatial resolution (Heinsch et al., 2003; Running et al., 2000, 2004). GPP estimates are derived from a light-use efficiency model as elaborated by Monteith (1972, 1977). In this model, net or gross photosynthesis is represented as the product of absorbed photosynthetically active radiation (APAR) and a LUE term. In the MODIS-GPP algorithm, APAR is the product of the fraction of incident photosynthetically active radiation (PAR) absorbed by vegetation (f_{APAR}) derived from MODIS spectral data (Myneni et al., 2002) and the incident PAR, estimated from incident shortwave radiation data from a General Circulation Model (GCM) (Heinsch et al., 2003). LUE is a biome-specific value representing optimal potential (i.e. under non-limiting conditions) of the vegetation for converting PAR to GPP. It is extracted from a look-up table and down-scaled to take into account the restraining effects on LUE of climatic variables (air temperature and vapour pressure deficit) from the GCM dataset. The inaccuracies inherent to this way of estimating LUE can account for much of the differences observed between satellite-based productivity estimates and field measurements (Martel et al., 2005; Running et al., 1999; Turner et al., 2003a). Several other authors have also proposed that LUE values used in ecosystem productivity algorithms do not adequately capture the spatial and temporal variability present across a region (Goetz & Prince, 1996, 1998; Turner et al., 2003b). Clearly, direct measurements of LUE from remote sensing data could improve estimates of C fluxes from terrestrial ecosystems at regional and global scales.

The photochemical reflectance index (PRI) was developed as a remotely-sensed indicator of LUE (Gamon et al., 1990, 1992). It uses narrow spectral bands to detect changes in leaf reflectance at 531 nm relative to a reference band that is usually located at around 570 nm and is not supposed to be affected by changes in short-term stress events. This change in the reflectance at 531 nm is created by the conversion of the xanthophyll cycle pigment violaxanthin to the de-epoxidized antheraxanthin and zeaxanthin as a way of dissipating excess light to protect the photosynthetic apparatus (Demmig-Adams & Adams, 1996; Demmig-Adams et al., 1998; Holt et al., 2005; Yamamoto, 1979). PRI has been correlated with both the epoxidation state of the xanthophyll cycle pigments and LUE in several field studies at the leaf and ecosystem levels (Gamon et al., 1992, 1997; Peñuelas et al., 1995, 1997; Trotter et al., 2002). Narrow-band spectral reflectance may also provide information on the ratio of carotenoids to chlorophyll a for detecting longer term stress effects and on total chlorophyll concentration for detecting plant nutrient status (Filella et al., 2004).

Eddy covariance (EC) flux towers are the most direct means of estimating LUE of terrestrial ecosystems. Correlations between PRI and ecosystem LUE were recently found when PRI was obtained from hyperspectral data acquired by aircraft (Rahman et al., 2001) and by helicopter-mounted sensors (Nichol et al., 2000). More recently, Rahman et al. (2004) used MODIS reflectance data from bands originally intended for ocean observations and calculated PRI over a temperate deciduous forest. They found a high correlation of MODIS-PRI with daily NPP that was derived from EC data. Given the major role boreal forests play in the global C cycle, it is important to analyze the extent to which MODIS-PRI is capable of estimating LUE in boreal ecosystems. To begin this effort, we selected a boreal aspen stand (*Populus tremuloides* Michx.) in Saskatchewan for which multi-year C flux data were available (Barr et al., 2004). Using flux and meteorological data from this aspen stand, the objectives of the current study were to determine (1) whether MODIS-PRI could track diurnal, day-to-day, seasonal, and/or annual variations in LUE; (2) the influence of view geometry on the PRI–LUE relationship; (3) the relative contribution of each PRI reflectance band to the overall signal; and (4) whether consistent PRI patterns were observable at a regional scale.

5. Conclusions

We found a strong correlation between a MODIS-sPRI, calculated using surface reflectances from bands 11 (531 nm) and 13 (667 nm), and flux tower-derived photosynthetic light use efficiency (LUE) of a boreal aspen stand. However, this relationship was robust only when MODIS scenes with backscatter reflectance were used to calculate sPRI. This test of our ability to measure ecosystem-level light use efficiency of boreal deciduous forests from space was limited by the small ranges and magnitudes of tower LUE values on the clear days when useful MODIS acquisitions could be obtained. Furthermore, the orbital parameters of the Terra and Aqua satellites restricted MODIS acquisitions to a 2.5-h period in early afternoon at our study site when LUE values were typically lower than they were earlier in the day. At the spatial resolution of a MODIS pixel (1 km^2), several factors appeared to confound the sPRI signal at 531 nm (e.g., sun/sensor geometry, background, atmosphere, canopy chlorophyll content) even for this homogeneous forest stand. Physiological interpretations of a MODIS-sPRI:LUE relationship using reference band 13 must be drawn with care, since the study was conducted only on a single site and because canopy structural and biochemical changes over time may both be involved in the reflectance signal. While PRI theory suggests that 531 nm reflectance should decrease with decreased LUE, we found increased reflectance not only at the 531 nm band, but at 551 nm, and 667 nm bands as well. All three of these bands are influenced by chlorophyll absorption.