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# Satellite detection of soil moisture related water stress impacts on ecosystem productivity using the MODIS-based photochemical reflectance index

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ABSTRACT

Satellite remote sensing provides continuous observations of vegetation properties that can be used to estimate global terrestrial ecosystem gross primary production (GPP). The Photochemical Reflectance Index (PRI) has been shown to be sensitive to vegetation photosynthetic light use efficiency (LUE), GPP and canopy water-stress. Here, we use the NASA EOS MODIS (Moderate Resolution Imaging Spectroradiometer) based PRI with eddy covariance $CO_2$ flux measurements and meteorological observations from 20 tower sites representing major plant functional type (PFT) classes within the continental USA (CONUS) to assess GPP sensitivity to soil moisture related water stress. The sPRI (scaled PRI) metric derived using MODIS band 13 as a reference channel ($sPRI_{13}$) shows generally higher correspondence with tower GPP estimates than other potential MODIS reference bands. The $sPRI_{13}$ observations were used as a proxy for soil moisture related water supply constraints to LUE within a satellite data driven terrestrial carbon flux model to estimate GPP ($GPP_{PRI}$). The $GPP_{PRI}$ calculations show generally favorable correspondence with tower GPP estimates ($0.457 \le R^2 \le 0.818$), except for lower $GPP_{PRI}$ performance over evergreen needleleaf forest (ENF) sites. A regional model sensitivity analysis using the $sPRI_{13}$ as a water supply proxy indicated that water restrictions limit GPP over more than 21% of the CONUS domain, particularly in drier climate areas where atmospheric moisture deficits (VPD) alone are insufficient to represent both atmosphere demand and water supply controls affecting productivity. Our results indicate strong potential of the MODIS $sPRI_{13}$ to represent soil moisture related water supply controls influencing photosynthesis, with enhanced (1-km resolution) delineation of these processes closer to the scale of *in situ* tower observations. These observations may provide an effective tool for characterizing sub-grid spatial heterogeneity in soil moisture related controls that inform coarser scale observations and estimates determined from other satellite observations and earth system models.


## 1. Introduction

Gross Primary Production (GPP), representing the sum of gross carbon ($CO_2$) uptake by plant photosynthesis, is a key component of the terrestrial carbon cycle (Potter et al., 1993; Yang et al., 2007). Accurate and reliable global estimation and monitoring of GPP is challenging due to a range of factors, including heterogeneity in vegetation conditions and environmental processes affecting photosynthesis. *In situ* observations from tower eddy covariance measurements have been used to track $CO_2$ exchange between terrestrial ecosystems and the atmosphere (Baldocchi et al., 2001); the associated tower measurements of net ecosystem $CO_2$ exchange (NEE) can be used to estimate GPP at the level of a local tower footprint (~1 $km^2$) and with daily temporal fidelity useful for detailed analysis of stand level processes. At present, over 650 flux tower sites are represented within the global FLUXNET network, providing detailed time series measurements of NEE, water vapor and energy exchange between terrestrial ecosystems and the atmosphere (Baldocchi et al., 2001). However, a major constraint of these observations for global GPP assessment and monitoring is their limited spatial representation and sampling bias relative to the global range of vegetation and climate conditions (Schimel et al., 2014).

Alternatively, satellite remote sensing provides spatially contiguous observations of vegetation and ecosystem properties that can be used for estimating GPP over a global domain (Running et al., 2004). Canopy light use efficiency (LUE) defines the rate of assimilation of canopy absorbed photosynthetically active radiation (APAR) into vegetation biomass, and provides a basis for estimating GPP using remote sensing

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(Chapin et al., 2002). The LUE concept, based on the original logic of Monteith (1972), is a commonly used modeling approach for estimating GPP, expressed as the product of APAR and LUE (Running et al., 2004; Potter et al., 1993; Xiao et al., 2004a, 2004b; Yuan et al., 2007). LUE is spatially and temporally dynamic according to various physical and environmental factors, including plant functional type (PFT), terrain, soil and environmental conditions (Madani et al., 2014). LUE is reduced from optimal or maximum levels for unfavorable environmental conditions, including water supply restrictions, excessive atmospheric moisture deficits, and cold temperatures (Goerner et al., 2011; Ahl et al., 2004).

The LUE modeling approach proposes a direct proportional relationship between GPP and APAR, with biophysical parameters that are readily derived from satellite remote sensing (Running et al., 2004). A variety of LUE models have been developed for monitoring GPP (Hilker et al., 2008). The MOD17 LUE algorithm (Running et al., 2004) is the basis for the NASA EOS MODIS (Moderate Resolution Imaging Spectroradiometer) global operational GPP product, which is derived using satellite based estimates of the canopy absorbed fraction of photosynthetically active radiation (fPAR), and ancillary daily surface meteorology inputs from global reanalysis data, including incoming solar radiation, atmosphere vapor pressure deficit (VPD), and minimum daily air temperature (Ta). The Terrestrial Carbon Flux (TCF) model (Kimball et al., 2009; Yi et al., 2013) uses a similar LUE logic, but includes additional frozen temperature and soil moisture (SM) related environmental constraints on the GPP calculations; the TCF model is the basis of the NASA SMAP (Soil Moisture Active Passive) Mission Level 4 Carbon (L4_C) model being used for global operational estimation of GPP and net ecosystem $CO_2$ exchange (NEE) using SMAP informed observations as primary environmental inputs (Entekhabi et al., 2014).

Photosynthesis and plant-atmosphere exchange of $CO_2$ and water vapor are strongly influenced by the supply of water to leaves from the soil *via* uptake by roots and atmosphere moisture deficit (Xiao et al., 2004a; Leuning et al., 2005). In the MOD17 algorithm, VPD provides the sole moisture control to photosynthesis; while VPD can explain the effects of atmospheric water demand regulating leaf stomatal closure and canopy gas exchange, there is no provision for evaluating impacts from soil water supply variations, which can introduce large model uncertainty (Leuning et al., 2005). The TCF model includes a representation of SM related water supply constraints to LUE and GPP, but a detailed understanding of regional and seasonal LUE and GPP responses to SM is lacking (Turner et al., 2003; Leuning et al., 2005; Xiao et al., 2004a).

A number of studies have demonstrated the potential of the Photochemical Reflectance Index (PRI) for better understanding LUE and potentially improving GPP estimation. The PRI, calculated as $(R_{531} - R_{ref}) / (R_{531} + R_{ref})$, uses canopy reflectance at 531 nm ($R_{531}$), which can detect changing pigments in the xanthophyll cycle (Gamon et al., 1992) from a reference reflectance ($R_{ref}$), giving the PRI the ability to detect changes in photosynthetic activity. Several studies have successfully tested alternative PRI reference wavelengths using both airborne and satellite based remote sensing. A 550 nm reference based PRI explained over 90% of diurnal variability in LUE for both nitrogen-stressed and irrigated sunflower crop canopies, but showed less LUE sensitivity under water stressed conditions (Gamon et al., 1992). A 570 nm reference based PRI was significantly correlated with midday photosynthetic rates for a range of vegetation types (Gamon et al., 1997). A 667 nm reference based PRI explained more than 75% of variability in tower-based LUE over boreal deciduous forest using MODIS top-of-atmosphere reflectances, which produced better PRI performance than atmospherically corrected MODIS data (Drolet et al., 2005).

The PRI has been used to account for leaf to canopy level temporal variations in LUE over a range of different climate and vegetation conditions (Garbulsky et al., 2008, Garbulsky et al., 2011; Gamon et al., 1992; Filella et al., 1996, 2009; Drolet et al., 2005, 2008; Goerner et al., 2011; Peñuelas et al., 2011). Previous studies using PRI as a LUE proxy to estimate productivity have yielded considerably more agreement with tower GPP estimates than the MODIS productivity algorithm (MOD17), especially during seasonal dry periods (Goerner et al., 2009; Garbulsky et al., 2008). MODIS-based PRI studies have also shown strong correspondence with tower-based LUE estimates under a range of conditions (Drolet et al., 2005; Drolet et al., 2008).

Alternatively, the PRI could be considered as a water stress indicator, distinguishing between well-watered and water stressed plants (Thenot et al., 2002). A weak relationship between the LUE of a water-limited canopy and the PRI was found by Gamon et al. (1992) when using a 550 nm reference reflectance band. Improved PRI relationships have also been found using longer wavelength references (Gamon et al., 1992). The PRI has also demonstrated sensitivity to diurnal changes in physiological indicators of water stress, such as stomatal conductance and stem water potential, though it is also sensitive to canopy structure and soil background variations (Suárez et al., 2008). Suárez et al. (2009) successfully used the remotely sensed PRI as a water stress indicator in annual and perennial irrigated crops. Time-series of airborne PRI observations normalized by incoming photosynthetically active radiation (PAR) also tracked changes in tree water status under different irrigation regimes (Suárez et al., 2010). Goerner et al. (2009) found that the MODIS-based PRI could track ecosystem LUE even during severe summer droughts in a Mediterranean forest, indicating PRI sensitivity to water stress. The PRI was also found to track observed inter-annual LUE variability associated with prolonged water stress in a water-limited Mediterranean pine forest (Moreno et al., 2012).

The PRI is sensitive to other factors in addition to canopy water stress, including species related differences in canopy structure and sensor observation view angles, which may limit PRI utility at regional or global scales (Barton and North, 2001; Hilker et al., 2010; Hernández-Clemente et al., 2011; Garbulsky et al., 2011). Continuous PRI observations from satellite optical and near infrared (NIR) remote sensing are strongly constrained over many areas by low solar illumination, cloud and atmosphere aerosol contamination, and sensor orbital swath gaps (Goerner et al., 2009; Hilker et al., 2009; Drolet et al., 2005, 2008). Fortunately, the PRI derived from MODIS is capable of relatively fine scale (~1-km resolution and daily time step) observations, while similar observations from MODIS sensors on both Terra and Aqua satellites may reduce PRI data gaps. However, there remains much uncertainty regarding relationships between the PRI and underlying environmental control factors at regional to continental scales. PRI utility as an indicator of spatially and temporally dynamic plant water stress factors affecting GPP is also unclear. The potential of the PRI to improve understanding and model representation of water supply constraints affecting LUE and GPP requires further investigation across a diversity of vegetation and climate conditions.

In this study, we compared several MODIS PRI formulations using different reference bands against tower site based surface soil moisture and GPP estimates spanning a continental US (CONUS) domain. The PRI formulation with the best performance was used as a surrogate for soil moisture (SM) related water supply controls on GPP in the TCF LUE model. PRI correlations with surface soil water content and eddy covariance $CO_2$ flux measurement based LUE estimates were also compared for tower sites representing diverse regional vegetation and climate conditions. Informed by MODIS PRI and tower biophysical observations, the TCF model was used to evaluate the relative importance of SM related water stress influencing GPP spatial and seasonal variations. A regional map of estimated mean daily GPP during the study period (2003–2006) was also derived using active SM related water supply controls in the TCF model defined using the best performing MODIS PRI formulation. An alternative model GPP map was generated using no active water supply control, while the difference between the two maps was used for assessing the regional impact of PRI and SM related water supply constraints to vegetation productivity.

## 2. Materials and methods

In this study, the potential of the PRI to represent LUE and GPP sensitivity to SM related water stress was investigated. The sensitivity of