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Potential of MODIS ocean bands for estimating CO_2 flux from terrestrial vegetation: A novel approach

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[1] A physiologically-driven spectral index using two ocean-color bands of MODIS satellite sensor showed great potential to track seasonally changing photosynthetic light use efficiency (LUE) and stress-induced reduction in net primary productivity (NPP) of terrestrial vegetation. Based on these findings, we developed a simple "continuous field" model solely based on remotely sensed spectral data that could explain 88% of variability in flux-tower based daily NPP. For the first time, such a procedure is successfully tested at landscape level using satellite imagery. These findings highlight the unexplored potential of narrow-band satellite sensors to improve estimates of spatial and temporal distribution in terrestrial carbon flux. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1640 Global Change: Remote sensing; 1694 Global Change: Instruments and techniques; 4806 Oceanography: Biological and Chemical: Carbon cycling. **Citation:** Rahman, A. F., V. D. Cordova, J. A. Gamon, H. P. Schmid, and D. A. Sims (2004), Potential of MODIS ocean bands for estimating CO_2 flux from terrestrial vegetation: A novel approach, *Geophys. Res. Lett.*, *31*, L10503, doi:10.1029/2004GL019778.

1. Introduction

[2] A high priority of the Global Change Research community is to locate and quantify terrestrial sources and sinks of carbon (S. C. Wofsy and R. C. Harris, unpublished manuscript, 2000) (see http://www.esig.ucar.edu/nacp). Traditionally two general approaches are used for this purpose: atmospheric transport modeling and ecosystem carbon exchange modeling [*Battle et al.*, 2000]. The accuracy and spatial resolution of both of these approaches are limited, mainly due to the scarcity of model inputs at requisite scales [*Potter et al.*, 1993; *Randerson et al.*, 2002]. A third approach - remote sensing, is currently considered a major tool in aiding both of these modeling approaches [*Running et al.*, 2000].

[3] NASA's most recent satellite-based sensor used for estimating global-scale terrestrial net primary productivity (NPP) is the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua platforms [*Justice et al.*, 1998]. MODIS-derived terrestrial NPP product (termed MOD17) for all land surface pixels has two phases [*Running et al.*, 2004]. One is an 8-day composite product called the PSN, which is equivalent to gross primary productivity (GPP = NPP + autotrophic respiration); the other is an annual NPP. A significant assumption in estimating MOD17 is that each biome has a fixed value for maximum light use efficiency (LUE), which is a measure of vegetation's ability to convert photosynthetically active radiation (PAR) to GPP [*Myneni et al.*, 2002]. This maximum LUE is then modified with functions driven by surface temperature and vapor pressure deficit obtained from coarse-resolution satellite-based weather data [*Running et al.*, 2004] thus producing a pseudo-dynamic "discrete field" LUE to estimate the MOD17 products.

[4] In this report we present the results of a novel approach for estimating "continuous field" LUE of terrestrial vegetation using the MODIS ocean bands #11 (bandwidth 526–536 nm) and #12 (546–556 nm) over a forested terrestrial ecosystem, in which all requisite data are obtained directly from satellite sensors. This approach is novel because MODIS ocean bands were not originally envisioned for this application, and data from ocean bands are not part of the standard processing protocol for terrestrial regions. Consequently, this approach has never before been tried from satellite-borne sensors.

[5] The scientific basis of our approach derives from an abundance of ecophysiological studies that have demonstrated the utility of narrow-band spectral reflectance at 531 nm for assessing the photosynthetic activity of terrestrial vegetation at spatial scales ranging from individual leaves to entire stands [*Gamon et al.*, 1992; *Peñuelas et al.*, 1995; *Gamon et al.*, 1997; *Nichol et al.*, 2000; *Rahman et al.*, 2001]. These studies have shown that the reflectance of green leaves at 531 nm and its immediate vicinity can often be related to the epoxidation state of the xanthophyll cycle pigments, a group of carotenoid pigments involved in foliar photosynthetic light regulation through the heat dissipation mechanisms of leaves. This process of heat dissipation can be detected as subtle changes in vegetation reflectance at 531 nm region [*Gamon et al.*, 1990].

[6] On the other hand, reflectance values at nearby wavebands (approximately 550 to 570 nm) are less affected by xanthophyll pigment conversion, and thus can provide a "reference" for normalizing the changing levels of reflectance at 531 nm. A spectral index, named the Photochemical Reflectance Index (PRI) has been developed that takes advantage of these characteristics. The formulation is $PRI = (\rho_{531} - \rho_{ref})/(\rho_{531} + \rho_{ref})$, where ρ represents reflectance at wavelengths (nm) expressed by the numeral subscripts, and *ref* represents a reference wavelength, typically 550 or

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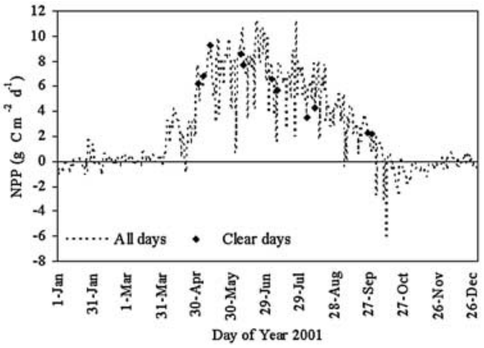

Figure 1. Daily NPP data from flux tower of MMSF for 2001. The 11 totally clear days when MODIS data and NPP were available are shown by the filled diamonds.

570 nm [*Gamon et al.*, 1992; *Peñuelas et al.*, 1995; *Gamon et al.*, 1997].

2. Data Processing and Analyses

[7] Due to its daily global coverage, MODIS provides a unique opportunity to explore the utility of the PRI over terrestrial regions. A central question for this study was whether these narrow wavebands, which were designed for sampling dark ocean regions, would be saturated over terrestrial landscapes. Fortuitously, forested regions, where the PRI signal is most likely to be useful, also happen to be relatively dark due to their strong absorption of visible radiation, thus reducing the probability of saturation.

[8] The study site was Morgan Monroe State Forest (MMSF), a secondary growth, 80-years old broadleaf deciduous forest in southern Indiana (39°19′N, 86°24′W, 275 m above sea level). This site is part of the AmeriFlux [*Baldocchi et al.*, 2001], a network of tower-mounted instruments for studying carbon balance of US ecosystems. From NASA's data gateway (Earth Observing System Data Gateway (EOSDG), http://edcimswww.cr.usgs.gov/pub/imswelcome), we downloaded MODIS (Terra) images for all days of 2001 covering the MMSF site. We chose 2001 because of the availability of a full annual coverage of MODIS imagery and also a complete set of validated and stability corrected flux data from the tower site. Ocean bands #11 and #12 were only available in radiometrically and geometrically corrected radiance values; or in 'Level-1B' according to NASA nomenclature (see the MODIS Web site at http://daac.gsfc.nasa.gov/data/dataset/MODIS/01_Level_1/index.html). NASA does not perform any further processing of these bands over land. We also downloaded daily reflectance images of land bands #1 and #2, which are R and NIR respectively.

[9] By visual inspection of the downloaded images and also using the flux-tower based daily incoming PAR data at hourly intervals, we selected the days that were totally cloud-free over the study region during the overpass time (10:30 A.M local time) as well as most of the day over the tower site. We found 11 such days during the green season (Figure 1). Even though relatively few in number, these green days were well distributed throughout the productive season of the year (early May to early October), including the early season of vigorous growth, mid season of stress and late season of leaf fall.

[10] Using the widely-used atmospheric correction algorithm '6S' [*Vermote et al.*, 1997] with proper relative spectral response (RSR) distribution function for bands #11 and #12, we derived surface reflectance values for these bands, and calculated the MODIS-derived PRI (or MODPRI) for each pixel, where MODPRI = $(\rho_{band\#11} - \rho_{band\#12})/(\rho_{band\#11} + \rho_{band\#12})$. For each pixel, we also calculated the Normalized Difference Vegetation Index (NDVI) using band #1 (R) and band #2 (NIR), where NDVI = $(\rho_{band\#2} - \rho_{band\#1})/(\rho_{band\#2} + \rho_{band\#1})$. Using these NDVI values of each pixel, we calculated fPAR, which is the fraction of PAR that is absorbed by vegetation and is expressed by the formula:

$$fPAR = 1.24 \times NDVI - 0.168\ldots \qquad (1)$$

This equation shows a linear relationship between NDVI and fPAR, and was derived using field data of NDVI and fPAR from a wide variety of ecosystems. Next, we calculated daily absorbed PAR (APAR) values for each pixel using the relationship:

$$APAR = fPAR \times \sum_{sunrise}^{sunset} PAR\ldots \qquad (2)$$

To spatially co-register the image products with tower-based daily NPP, we then cut an area covering 3 × 3 pixels centered at the tower's coordinates, from the above-mentioned PRI and NDVI images, because studies have shown that based on wind speed and direction, the tower's flux footprint is almost entirely contained within, and also quite evenly distributed over, that area [*Schmid et al.*, 2000]. Since the tower-based flux instruments provide net ecosystem productivity (NEP = NPP - heterotrophic respiration) rather than NPP, we used Biome-BGC model [*Running et al.*, 2000] to estimate heterotrophic respiration in order to calculate the daily NPP. Our decision to use the daily NPP values was based on three reasons, 1) daily NPP is the value used to synthesize the annual carbon uptake by ecosystems, 2) NPP includes vegetation photosynthesis and

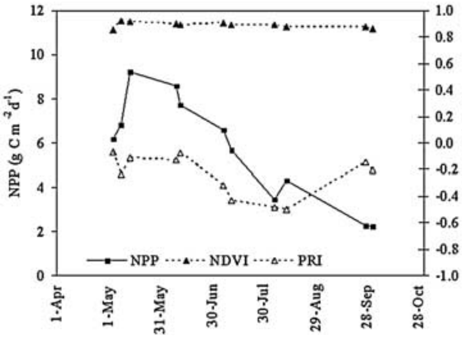

Figure 2. MODIS-derived NDVI and PRI from the averaged values of the flux tower footprint (3 × 3 pixels) in contrast to the daily NPP from the tower. NDVI saturated to a value of 0.9 quite early in the productive season (by May 8th). On the other hand, PRI did not show any saturation and varied throughout the season.

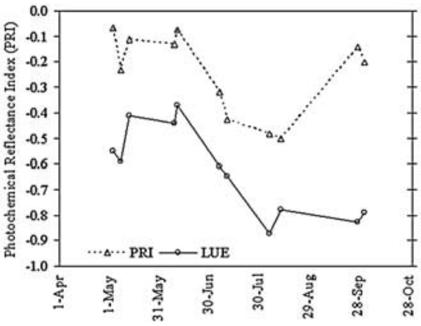

Figure 3. The seasonal trend in PRI and LUE (micro-mol/micro-mol) for the leaf-on season. PRI and LUE showed nearly identical temporal trends. Specifically, PRI was able to track the mid-season reduction in LUE.

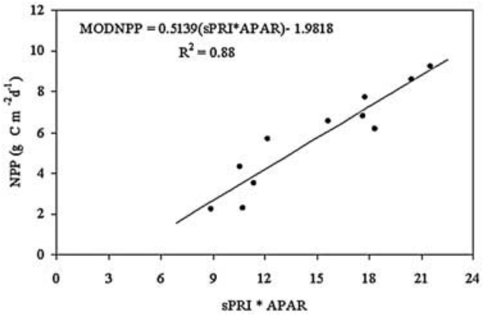

Figure 4. Regression result of tower-based daily NPP vs. (sPRI × APAR) for the 11 clear days. Since both sPRI and APAR are per-pixel products, the encouraging result of this model shows promise towards providing a truly "continuous field" approach to estimating terrestrial carbon flux.

respiration, both of which are regulated by stress levels, and 3) we found that the tower-based hourly NPP during the MODIS overpass time and the daily NPP were linearly correlated with a Pearson's correlation coefficient value of $r = 0.93$.

[11] The NDVI values of the nine pixels for a given image were very similar to each other, as was also the case for PRI. This was expected because the tower has been established on that spot considering the topographic similarity and vegetation homogeneity of the surrounding areas [*Schmid et al.*, 2000]. So, we averaged the NDVI and PRI values of these 9 pixels and considered these averaged values as representative of the tower footprint.

[12] Comparison of these averaged PRI, NDVI and tower-based daily NPP values showed that the NDVI attained a threshold value ('saturation') of almost 0.9 by May 8th, an early date for greening-up, and stayed at that level for the rest of the productive season (Figure 2). Many previous studies have shown this saturation problem of NDVI at a relatively early stage of growing season [*Baret and Guyot*, 1991]. On the other hand, PRI varied dynamically throughout the season, just as NPP did, closely tracking a mid-season (July–August) reduction in NPP associated with stress due to summer drought. As a further test of relationship between PRI and NPP, we compared these time series of PRI with that of the tower-based LUE values that were obtained from dividing daily NPP by daily APAR (Figure 3). PRI and LUE showed nearly identical temporal trends. These three properties of PRI, i.e., 1) the lack of saturation throughout the growing season, 2) ability to track stress and 3) similarity in temporal trend with LUE, support the hypothesis that satellite-based PRI is able to track changes in landscape-level photosynthetic activity. Based on these observations, we used a modified form of Monteith equation to derive NPP from PRI.

[13] The widely used Monteith equation [*Monteith*, 1977] for modeling daily NPP from daily APAR and LUE is a simple one: NPP = LUE × APAR. Based on the results shown in Figure 3, we generated a scaled value of PRI that we hypothesized to function as a surrogate for LUE. Since PRI is a normalized index and its value can, in theory, range from -1 to $+1$, we transformed it into an 'efficiency' term by a simple algebraic manipulation of adding 1 to each PRI value and dividing the result by 2. This scaled PRI (sPRI) has a range of 0 to 1. Following Monteith equation we multiplied the sPRI with daily APAR and examined the relationship of this product with tower-based daily NPP. The regression analysis (Figure 4) revealed a linear relationship between daily NPP and the (sPRI × APAR) term, which could explain 88% of temporal variability in NPP. The resulting regression equation was:

$$NPP = 0.5139(sPRI \times APAR) - 1.9818\ldots \tag{3}$$

In this equation, the units of NPP are: grams of Carbon per square meter per day (g C m^{-2} d^{-1}), those of APAR are: mol per day (mol d^{-1}), and sPRI is a unit-less ratio. This relationship indicates considerable potential for this novel satellite-based approach of incorporating narrow-band MODIS signals not previously applied to terrestrial studies. For the first time, a photosynthetic model utilizing only two image-based products from satellite-borne sensors is shown to track the variations in daily NPP with a substantial accuracy throughout the growing season.

[14] A comparison between PSN of the tower footprint (average of 3 × 3 pixels), tower-based daily NPP and the NPP from the above equation (3), which we termed MODNPP, along with the tower-based GPP, shows the capability of the MODNPP for tracking daily NPP

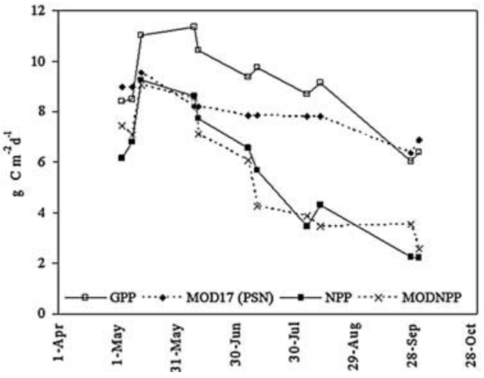

Figure 5. Comparison of tower-based daily GPP, NPP and MOD17 (PSN) with the MODNPP. MODNPP closely followed the seasonal course of flux tower-based NPP. This close match in seasonal pattern, including a dip associated with drought, was not seen in the MOD17 product.

(Figure 5). We also showed tower-based GPP in this figure since PSN is designed to be equivalent to GPP, rather than NPP. One weakness of PSN here was that even though it overestimated tower-based GPP at the beginning and ending of the growing season, it consistently underestimated GPP during the leaf-on season. These anomalies are topics of active research [*Running et al.*, 2004], but one factor may be the exclusive use of R and NIR bands in calculating PSN, which may be affected by the saturation factor similar to that shown in Figure 2.

3. Discussion and Conclusions

[15] Incorporating the temporally dynamic PRI appears to improve the fidelity of modeled fluxes. Remarkably, the model, which was derived from ocean and land bands of MODIS, closely followed the seasonal course of NPP, which was derived from the flux tower. This close match in seasonal pattern, including a dip associated with drought, was not seen in the NDVI or the MOD17 product. Recent studies indicate that the assumptions in MOD17 of spatial and temporal invariability for biome-specific physiological parameters, and also its dependence on coarse resolution weather data may have compromised some of its robustness [*Turner et al.,* 2003; *Running et al.*, 2004]. On the other hand, the simple model discussed in this report is solely based on remotely sensed imagery and is truly variable in spatial and temporal aspects, i.e., per pixel. Rather than any a priori assumptions, lookup tables, or literature values, it uses seasonally changing data obtained from each pixel, providing a dynamic, "continuous field" approach to estimating carbon fluxes.

[16] The underpinning of our approach is based on a recent history of ecophysiological studies that has not yet been extended to landscape level using satellite data. Because NDVI is structurally-driven and PRI is physiologically-driven spectral indices, the two appear to be complementary in estimating photosynthetic status of green vegetation. We demonstrated here that combining these two indices in a physiologically meaningful fashion should reveal changing photosynthetic activity at landscape level, detectable from operational satellite sensors. With further validation, this approach has the potential of augmenting the current global-scale MOD17 to improve estimates of the spatial and temporal distribution of NPP and consequently the terrestrial sources and sinks of carbon. We think this approach would be most useful in heavily vegetated areas subjected to periodic stress, where NDVI is unable to detect short-term stress events (e.g., drought) due to saturation, but PRI can capture the subtle changes in leaf physiology.

[17] For further validation, this approach should be tested on a wide variety of terrestrial ecosystems, and should be supplemented by modeling and mid-range empirical studies that could bridge the vastly different spatial scales of the typical field study and a MODIS pixel. Fortunately, the established flux tower network (FluxNet) and the growing spectral sampling networks (SpecNet) exist to provide further tests of this approach. A primary recommendation emerging from this work is the need to provide processed and quality controlled MODIS ocean band data products over land regions.

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