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Potential of MODIS EVI and surface temperature for directly estimating per-pixel ecosystem C fluxes

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[1] We tested the potential of estimating per-pixel gross primary production (GPP) directly from the MODIS enhanced vegetation index (EVI) and respiration directly from MODIS surface temperature (MOD11). Carbon flux data were obtained from 10 eddy covariance tower sites representing a wide range of North American vegetations. The correlation between across-site tower GPP and EVI was comparable ($r = 0.77$) to that between tower GPP and MOD17-GPP ($r = 0.73$), suggesting that EVI could be used to provide reasonably accurate direct estimates of GPP on a truly per-pixel basis. There was also a strong relationship ($r^2 = 0.67$) between respiration and surface temperature of dense vegetation, suggesting that estimation of net ecosystem exchange (NEE) may be possible with relatively simple pixel based models, at least for some vegetation types. **Citation:** Rahman, A. F., D. A. Sims, V. D. Cordova, and B. Z. El-Masri (2005), Potential of MODIS EVI and surface temperature for directly estimating per-pixel ecosystem C fluxes, *Geophys. Res. Lett.*, *32*, L19404, doi:10.1029/2005GL024127.

1. Background

[2] Remote sensing (RS) is currently used as a major tool for estimating spatially distributed carbon (C) balance of ecosystems [*Running et al.*, 2004]. The most versatile, operational and global-scale RS product, termed MOD17, provides gross and net primary production (GPP and NPP) using imagery from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) [*Running et al.*, 2000, 2004]. Two other recent RS-based models for GPP or NPP are the Vegetation Photosynthesis Model (VPM) [*Xiao et al.*, 2004, 2005] and the MOD-Sim-Cycle model [*Hazarika et al.*, 2005]. Unfortunately, all three of these RS-based models have limitations and none of them provide truly per-pixel GPP or NPP outputs.

[3] In addition to MODIS-derived 1-km leaf area index (LAI), MOD17 uses other coarse resolution (1° latitude × 1.25° longitude) weather inputs and is essentially an interpolated and 'pseudo-continuous,' product, i.e., not truly per-pixel. The VPM is a 'light use efficiency' (LUE) model where LUE is modeled using apparent quantum yield for different biome types and then constrained by a leaf water status index and coarse resolution temperature data. The MOD-Sim-CYCLE model uses MODIS-derived LAI to constrain a process model Sim-CYCLE [*Ito and Oikawa*, 2002] and lookup table based coarse resolution biophysiological variables to produce annualized NPP at a spatial resolution of $0.5° \times 0.5°$ cells. Recent studies suggest that the use of coarse resolution weather data and 'lookup table'-based ecophysiological inputs may introduce significant errors to modeled GPP or NPP [*Turner et al.*, 2003, 2005; *Heinsch et al.*, 2005; *Zhao et al.*, 2005].

2. Justification of Our Approach

[4] We investigated the potential of directly estimating per-pixel GPP from the enhanced vegetation index (EVI, a greenness index). We chose EVI instead of the widely used normalized difference vegetation index (NDVI, another greenness index) because contrary to NDVI, EVI has been shown not to saturate at high vegetation densities [*Huete et al.*, 2002]. Also, *Xiao et al.* [2004] have recently shown that for a deciduous site GPP correlated better with EVI ($r \approx 0.68$) than with NDVI ($r \approx 0.45$).

[5] It is usually assumed that greenness indices are insufficient to estimate GPP because of variability in LUE. Yet, a per-pixel estimate of LUE is not currently available. It requires inputs of environmental variables that are often available only as averages over large areas, as noted above. Therefore, we explored the extent to which GPP could be estimated without direct consideration of variation in LUE.

[6] We used 16-day composite data for both flux and EVI because MODIS EVI data are available in a 16-day composite format. We hypothesized that this 16-day period would be long enough to smooth out short-term variations in environmental variables that might result in short term fluctuations in LUE. On the other hand, we found that the 16-day period has the advantage of being long enough to allow for some variation in EVI from one period to the next.

[7] Respiration is much more strongly influenced by temperature than is photosynthesis. In this paper, we also examine the extent of a general relationship between ecosystem respiration and MODIS surface temperature (MOD11) that could be used for direct estimation of per-pixel respiration. To our knowledge, this is the first study to derive generalized across-biome relationships between the time series of MODIS-derived EVI with GPP, and surface temperature with respiration flux.

3. Sites, Data and Methods

3.1. Variability of the Study Sites

[8] We used C flux data from 10 AmeriFlux tower sites (Table 1). These sites represent a wide diversity of natural vegetation across North America, with relative uniformity

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Table 1. Carbon Flux and MODIS Data From These 10 Ameriflux Sites Used in This Study[a]

Site name	Vegetation Type	Latitude	Longitude	Years	Methods References
Blodgett	Evergreen needleleaf forest	38.895	120.633	2000–2002	*Goldstein et al.* [2000]
Niwot Ridge	Evergreen needleleaf forest	40.033	105.546	2000–2003	*Monson et al.* [2002]
Northern Old Black Spruce (NOBS)	Evergreen needleleaf forest	55.879	98.481	2000–2004	*Goulden et al.* [1997]
Wind River	Evergreen needleleaf forest	45.821	121.952	2000, 2002–2004	*Paw U et al.* [2004]
Howland forest	Evergreen needleleaf forest	45.204	68.740	2000–2003	*Hollinger et al.* [1999]
Harvard forest	Deciduous broadleaf forest	42.538	72.171	2000–2003	*Goulden et al.* [1996]
Morgan Monroe State Forest (MMSF)	Deciduous broadleaf forest	39.323	86.413	2000–2001	*Schmid et al.* [2000]
Lethbridge	Grassland	49.708	112.940	2000–2001	*Flanagan et al.* [2002]
Tonzi	Woody savanna	38.432	120.966	2001–2004	*Xu and Baldocchi* [2004]
Sky Oaks	Semi-arid shrubland	33.375	116.621	2000–2002	*Sims et al.* [2005]

[a] For details of the methods used at each site see the "Methods References."

of vegetation characteristics for a 3 km radius around the tower and availability of corrected diurnal C flux data concurrent with MODIS images. The time span includes two La Niña years (2000–2001) and three moderately El Niño years (2002–2004) (see http://www.cdc.noaa.gov/ENSO/enso.mei_index.html), thus incorporating substantial climatic variability in our data.

[9] The five evergreen needleleaf forest sites represent considerable variation in regions, climate and species composition. Blodgett is a young ponderosa pine forest in the Sierra Nevada of Western USA with moderate winters and relatively dry summers. Wind River is a 500-yr natural undisturbed old-growth, Douglas-fir and Western hemlock ecosystem with higher rainfall than at Blodgett. Niwot Ridge is a subalpine temperate coniferous forest in the Rocky Mountains, with more extreme winters in comparison to the Western sites. The Northern Old Black Spruce (NOBS) site in Canada and Howland forest in Maine consist of mixed evergreens and relatively open canopies that allow a greater development of understory species.

[10] The two deciduous forest sites are characteristic of the Eastern deciduous forests of the USA, with diverse species composition. Morgan Monroe State Forest (MMSF) in Indiana is a warmer site than the Harvard forest in Massachusetts. The Lethbridge site in Canada is representative of the short grass prairies east of the Rocky Mountains whereas the Tonzi is representative of the Oak savannas in the foothills of the Sierra Nevada Mountains of California. Finally, Sky Oaks in Southern California is a sparse, semi-arid site with Mediterranean climates, representing US Southwestern shrublands.

3.2. MODIS Spectral Data

[11] EVI and Land surface temperature (LST) data were obtained from the 7 × 7 km subsets of MODIS products available at Oak Ridge National Laboratory's Distributed Active Archive Center (DAAC) web site (http://www.modis.ornl.gov/modis/index.cfm). We extracted average values for the central 3 × 3 km area within the 7 × 7 km cutouts to better represent the flux tower footprint [*Schmid*, 2002]. We used only EVI data that had aerosol values listed as "low" and the "usefulness" value listed as greater than 8 (on a scale of 0–10) and LST data that were listed as cloud free.

[12] The MOD17 GPP data (collection 4.5) from the University of Montana's NTSG ftp site (ftp.ntsg.umt.edu/pub/MODIS) were available as 8-day composites. We averaged two consecutive periods of these data in order to conform to our 16-day EVI and flux data. Similar to the EVI, we used average values of MOD17 GPP for the central 3 × 3 km area surrounding each tower site for comparison with the tower flux data.

3.3. Calculation of Tower-Based C Fluxes

[13] Measurements of CO_2 flux exchange in each site were made with the eddy covariance technique (for references see Table 1). When gap filled GPP estimates were available from the site databases we used these values. In other cases, we estimated daytime respiration (R) using the following relationship [*Sims et al.*, 2005]:

$$R = R_n * e^{\left(k^*(T_a - T_n)\right)} \tag{1}$$

where R_n is the nighttime respiration rate, T_n is the mean nighttime air temperature corresponding to the data points used to calculate R_n, T_a is the air temperature at the time of estimation of R, and k is a coefficient relating respiration to air temperature (0.07), which results in a Q_{10} of 2 [*Goulden et al.*, 1996; *Reichstein et al.*, 2002]. GPP was then estimated from the following equation:

$$GPP = NEE - R \tag{2}$$

where NEE is the net ecosystem(vegetation and soil) exchange of CO_2 measured by the flux tower, and used in our analysis.

[14] To calculate 16 day averages for non gap-filled data, all GPP data for each half hour (or hour, as available) interval over the 24 hour cycle were averaged over each 16-day period. Then these half hourly (or hourly) averages were summed to give a daily total flux. Data were not used when there were fewer than 6 good data points in each 16-day period. Similarly, 16 day averages of midnight to 4 AM values of R_n were calculated to represent nighttime respiration.

4. Results and Discussion

[15] To develop an ecosystems-wide empirical relationship, we aggregated data from all sites to produce 'EVI vs. C-flux' scatter plots and calculated Pearson's correlation coefficient (r) between EVI and fluxes (Figure 1). EVI was better correlated with GPP (Figure 1b) than with NEE (Figure 1a). The EVI-GPP relationship was stronger when only the deciduous vegetation types (deciduous forests, grasslands and savannas) were included (r = 0.89 vs. r = 0.77 for all sites) since some of the evergreen vegetation sites did not show significant relationships within the site. However, the data for these evergreen sites still fell on the overall relationship. A scatter plot of the averages and

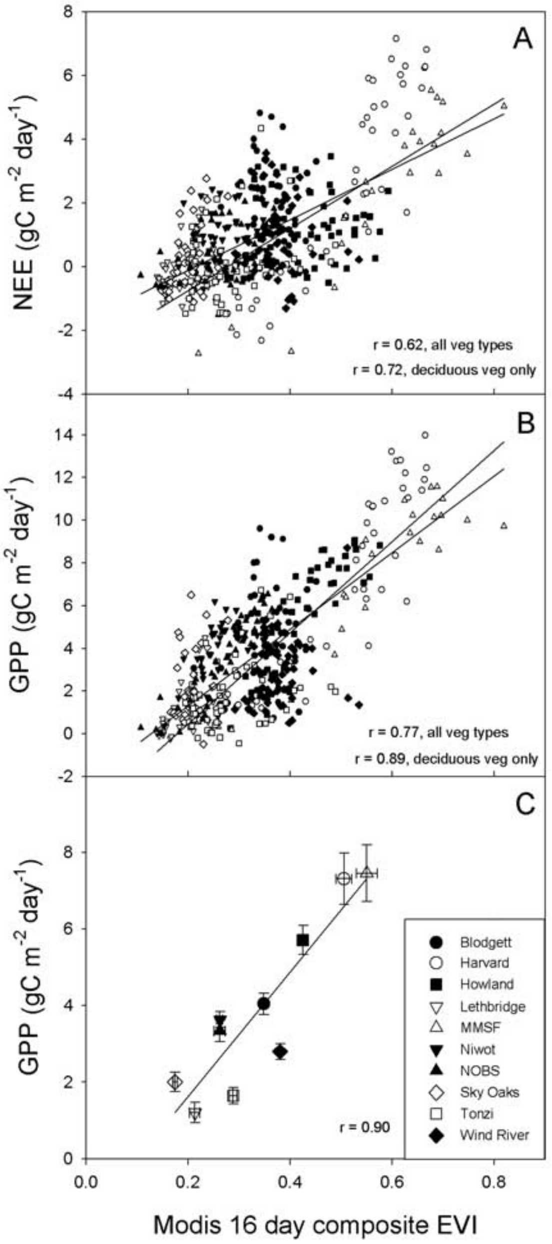

Figure 1. Relationships between 16 day averages of net and gross ecosystem CO_2 flux and MODIS 16 day composite EVI data for the 10 sites in this study. Only data from periods when temperatures were high enough to allow the vegetation to be actively photosynthesizing are shown. Means ± standard errors for each site are shown in 1C. Pearson's correlation coefficient (r) values are listed on the plots ($p < 0.001$ for all relationships). Deciduous vegetation sites are Harvard, MMSF, Lethbridge and Tonzi.

standard errors of the across-site data further clarifies this overall relationship (Figure 1c). Consequently, it should be possible to use the overall relationship to estimate GPP with fairly high accuracy at the broad scale.

[16] The weaker relationship between EVI and NEE, than for GPP, probably results from variation in respiration that was not correlated with vegetation greenness. The comparison between nighttime respiration and surface temperature shows that a large portion of the variation in respiration was probably accounted for by variation in surface temperature rather than greenness (Figure 2). In fact, for the densely vegetated sites the relationship between R_n and MODIS nighttime surface temperature was remarkably consistent (Figure 2, closed symbols). The Q_{10} value for the closed-canopy vegetations was 1.93, very similar to the value reported in literature [*Goulden et al.*, 1996]. This exponential relationship had a coefficient of determination (r^2) value of 0.67. Exclusion of data from one of the sites (Wind River), which showed unusually large scatter, increased the r^2 to 0.77 but had little effect on the fitted equation.

[17] The sparse-canopy vegetation, on the other hand, had much lower respiration rates for a given temperature, and the relationship of respiration with temperature was much weaker (Figure 2, open symbols). Whereas respiration was primarily a function of temperature for the closed canopy sites, it was very likely influenced by the density of vegetation and soil water content as well for the sparse canopy sites. These relationships expressed in Figure 2 demonstrate the possibility of estimating respiration of closed-canopy vegetations from MODIS-derived surface temperature, and also the limitation of this method for sparse-canopy vegetation.

[18] The relationship between MOD17 GPP and flux tower based GPP had an r value of 0.73 for all vegetation types (Figure 3). Consequently, EVI (with a correlation to tower GPP of 0.77) was as good an indicator of GPP as the MOD17 GPP product and showed the potential of producing a truly per-pixel output. Additionally, MOD17 overestimated GPP at low values of tower GPP and underestimated it at high values. Similar to the EVI-GPP relationship, the MOD17 GPP vs. tower GPP correlation was stronger (r = 0.85) when only deciduous vegetation was included in the calculation.

5. Conclusion

[19] Even though MOD17 is the only global-scale product currently capable of delivering GPP and NPP in high

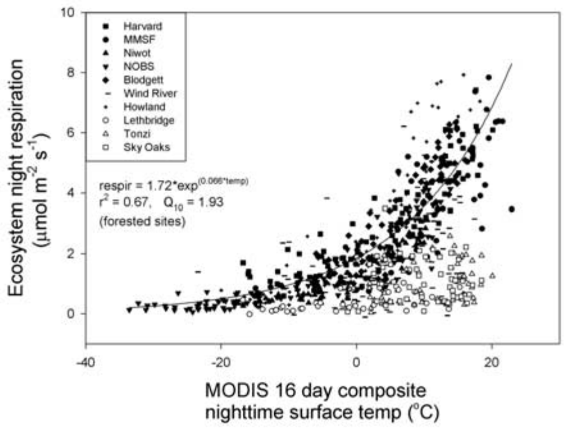

Figure 2. Relationships between 16 day means of dark respiration (midnight to 4 AM) and MODIS (Terra) nighttime surface temperature (MOD11) for the 10 sites in this study. Data include the full annual cycle for all sites. Coefficient of determination (r^2) for the exponential relationship is listed on the plot.

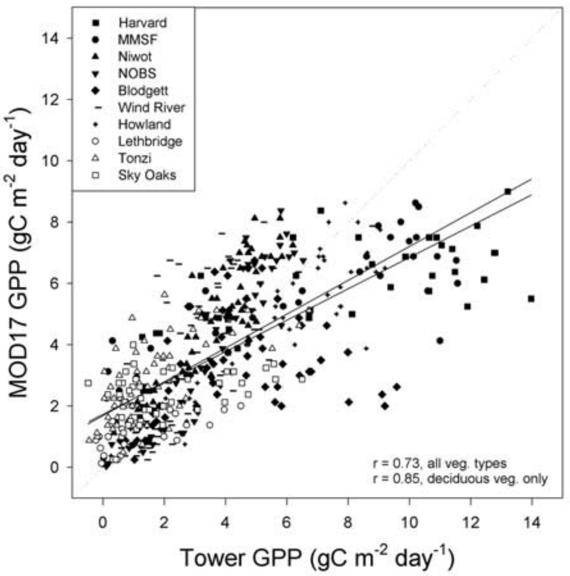

Figure 3. Relationship between the MOD17 estimate of GPP and eddy covariance tower measured GPP (both 16 day means) for the 10 sites in this study. Deciduous vegetation sites are Harvard, MMSF, Lethbridge and Tonzi.

temporal and spatial resolutions unmatched by any other single measure, recent validation studies show that it has considerable errors. These errors are due to problems associated with inputs [*Turner et al.*, 2003, 2005; *Zhao et al.*, 2005], use of lookup tables [*Heinsch et al.*, 2005; *Turner et al.*, 2005] or even the MOD17 algorithm itself [*Heinsch et al.*, 2005]. Two other recent RS based GPP or NPP models are also 'pseudo-continuous' and have significant limitations for routine operational use.

[20] The strong EVI-GPP correlation shown in this paper demonstrates that a simple regression model, based solely on remotely sensed per-pixel input, has the potential of being used as an alternative method to estimate GPP of wide ranging vegetation types. This method is easy to compute with routinely available EVI data, does not depend on any external input such as meteorology or lookup tables for calculation of LUE, and does not require any spatial extrapolation of inputs or outputs. And a comparison between Figures 1b or 1c and Figure 3 indicates that the potential of this method for estimating terrestrial GPP is at least as good as that of the MOD17. In addition, the strong relationship between surface temperature and respiration for densely vegetated sites suggests that it may be possible to also calculate NEE with relatively simple, pixel based models as well, at least for some ecosystems.

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