Remote estimation of carbon dioxide uptake of terrestrial ecosystems

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Abstract

The estimation of the carbon balance in ecosystems, regions, and the biosphere is currently one of the main concerns in the study of the ecology of global change. Current remote sensing methodologies for estimating gross primary productivity are not satisfactory because they rely too heavily on (i) the availability of climatic data, (ii) the definition of land-use cover, and (iii) the assumptions of the effects of these two factors on the radiation-use efficiency of vegetation (RUE). A new methodology is urgently needed that will actually assess RUE and overcome the problems associated with the capture of fluctuations in carbon absorption in space and over time. Remote sensing techniques such as the widely used reflectance vegetation indices (e.g., NDVI, EVI) allow green plant biomass and therefore plant photosynthetic capacity to be assessed. Nevertheless, detecting how much of this capacity is actually realized is a much more challenging goal. The Photochemical Reflectance Index (PRI) derived from freely available satellite information (MODIS sensor) presented an exponential relationship with the RUE. Thus, we show that it is possible to estimate RUE in real time and therefore actual carbon uptake at ecosystem, regional, and biosphere levels using the PRI. This conceptual and technological advancement avoids the need to rely on either the sometimes unreliable maximum RUE for each ecosystem, hard-to-obtain climate data, or on imprecise land-use/land-cover data.

Introduction

The scientific community is devoting huge amounts of time and resources to assessing the global carbon budget in a context of climate change (Boisvenue and Running, 2006, Ciais et al., 2005, Schulze, 2006). Current remote sensing methodologies for estimating gross primary productivity mostly depend on absorbed radiation and the efficiency of conversion into carbon-based compounds as proposed in Monteith's model (Monteith, 1977). Most methodologies rely heavily on (i) the availability of climatic data, (ii) the definition of land-use cover to estimate the radiation-use efficiency of the vegetation (RUE), and/or (iii) assumptions of the effects of both these previous factors on the RUE. These methodologies are thus over-dependent on the availability of climatic data, the quality of land-cover data, and assumptions regarding RUE (Heinsch et al., 2006).

Recent scientific work at leaf and plant scales reveals that it is possible to estimate radiation-use efficiency remotely by using a photochemical reflectance index (PRI) (Gamon et al., 1992, Peñuelas et al., 1995, Peñuelas et al., 1997). The PRI derived from new breed narrow-band spectroradiometers are increasingly being used as photosynthetic performance indicators at ecosystem level (Asner et al., 2004). By complementing the NDVI estimation of green biomass -and therefore of potential productivity (Gamon et al., 1995)- with PRI it is now possible to improve assessments from airborne sensors of the carbon uptake in many of the world's ecosystems (Nichol et al., 2002, Nichol et al., 2006, Rahman et al., 2001). The global coverage of satellites has dramatically improved our capacity to extend PRI-based estimations of vegetation radiation-use efficiency and carbon fluxes to all areas of the globe. However, the highly interesting possibilities offered by satellite images are still little used and under evaluation (Drolet et al., 2005, Rahman et al., 2004). Net Primary Productivity estimations for ecosystems with low seasonality in their radiation interception (e.g., evergreen forests) but high seasonality in their carbon absorption could especially benefit from this approach. In other ecosystems, where high seasonality in the leaf-area index is the main driver of carbon absorption, the traditional NDVI (Tucker et al., 1985)or EVI (Sims et al., 2006b) approach seems robust enough for arriving at a good estimation of the GPP (Sims et al., 2006a).

We evaluated the worth of the PRI derived from satellite MODIS sensors as an estimator of the radiation-use efficiency in a Mediterranean forest in which (a) seasonal variation in radiation interception is very low and (b) carbon absorption has important seasonal fluctuations that are mainly determined by water deficits during summer (Rambal et al., 2003) and very short periods of low temperatures in winter (Ogaya and Peñuelas, 2003), which provoke significant periods of very low photosynthesis. Because of the negligible changes in structure and leaf area index and thus in radiation interception, it is of great importance in this forest to have accurate measurements of radiation-use efficiency. This is a paradigmatic case in which to look for an alternative to the use of intercepted radiation as the only remote sensing input driving global models estimating carbon fluxes, and therefore, a leading case in which to produce a real time estimation of carbon absorption by vegetation.

Materials and Methods

We analyzed eddy covariance data of carbon fluxes and MODIS (Moderate Resolution Imaging Spectroradiometer) remote sensing data in the Mediterranean forest of Castelporziano in central Italy (41º 42´ lat; 12º 22´ long; mean annual temperature 15.6 ºC; mean annual precipitation 767 mm) for the period January 2001- December 2002. The vegetation is a 10-meter-tall broadleaf evergreen forest mainly dominated by holm oak (*Quercus ilex* (Tirone et al., 2003)).

We used the PRI as a remotely sensed estimator of the RUE in the model proposed by Monteith (Monteith, 1977).

$$\mathrm{RUE} = \mathrm{GPP}/\mathrm{APAR} \qquad (1)$$

where RUE is the radiation-use efficiency, GPP is the gross primary productivity, and APAR is the photosynthetic active radiation absorbed by the vegetation, as calculated by the product of fPAR (the fraction of the PAR absorbed by the canopy, estimated from the NDVI (Myneni et al., 2002)) and the PAR derived from the eddy covariance tower data. We used the spectral index EVI as an alternative linear estimator of the fPAR (Xiao et al., 2005). The GPP was estimated from the total CO_2 fluxes from the eddy covariance tower (Valentini et al., 2007) and ecosystem respiration and storage estimated (Papale et al., 2006, Reichstein et al., 2005) and climate data at 30 minutes resolution.

An average of the GPP and PAR half-hour values was calculated for days having MODIS surface reflectance data (MODO9A1 band 1 (620-670 nm), band 2 (841 - 876 nm), band 3 (459 - 479 nm)). These images consist of 8-day composites constructed from the daily surface reflectance for specific dates. The Normalized Difference Vegetation Index (NDVI = (band 2- band 1)/(band 2 + band 1) and the Enhanced Vegetation Index (EVI = 2.5*(band 2 - band 1)/(band 2+ 6*band 1-7.5* band 3) were calculated from those images and assigned to those dates. The temporal resolution of the analysis is 8 days, which corresponds to that of the MODO9A1 images. Theoretically, this represents 46 days per year; however, we only obtained data for 33 days in 2001 and 17 in 2002 due to a lack of data for one or other of the sources. For all the MODIS data, quality flags were checked to discard low quality images.

To calculate the Photochemical Reflectance Index (PRI = (band 11- band 12)/ (band 11 + band 12)), we extracted the MODIS daily calibrated radiance (MODIS Terra L1b - MODO21km V005) for bands 11 (526-536 nm) and 12 (546-556 nm) for the pixel (1 x 1 km) that included the tower. We used for the calculation the same specific dates as for the NDVI and EVI calculations. The atmospheric effects on bands 11 and 12 were similar because they are positioned closely together in the spectrum. Moreover, atmospheric transmissivity in this part of the spectrum is very high and stable and thus its atmospheric correction would have very little effect (Vermote et al., 2002). On comparing the surface reflectance (MODO9A1) and the calibrated radiance (MODO21KM) for the years 2001-2004 for band 4 (545 – 565 nm), evidence emerged that a linear adjustment between them exists (r^2=0.76, n=68, p<0.0000001). Thus, we considered that the calibrated radiance at these bands could be used without atmospheric correction in the calculation of a normalized spectral index such as the PRI.

We evaluated the PRI as an estimator of the RUE (eq. [1]) and then parametrized the relationship by means of a subset of the data and a linear regression analysis for 2002. We applied the parametrized model to the rest of the data as per the model proposed by Monteith and compared it with the estimations regularly made by the MODIS team (Heinsch et al., 2003) (MODIS17A2, version 4.8). We compared the final GPP product for both methodologies, however we cannot rule out differences in both estimations due to the use of different PAR data and different fPAR estimations. Fair correlations were found between incident radiations measured by the towers and those derived from the global climate model (GEOS-4) included in the MODIS GPP product (Heinsch et al., 2006).

Results and Discussion

GPP ranged from 1.5 to 8 g C m^{-2} d^{-1} (Fig. 1a), with minimum values occurring mainly in winter and local minimum in summer. Radiation absorption, as estimated from NDVI and EVI, were very stable throughout the year (Fig. 1b). The GPP/APAR ratio ranged between 0.3 and 1.7 g C MJ^{-1}, with minimum values in summer and maximum values in winter or spring (Fig. 1c). The seasonality of the PRI was similar to that of the GPP/APAR ratio throughout the study period. The PRI was a good reflection of seasonal changes in the timing and magnitude of GPP/APAR (Fig. 1c). The seasonal coefficients of variation (standard deviation/mean) were only 3% for NDVI and 12% for EVI, but reached 66% for PRI and 46% for GPP/APAR.

The PRI was a good exponential estimator of the GPP/PAR ratio (Fig. 2c). The NDVI was not correlated and the EVI was slightly negatively correlated to the GPP/PAR, although the latter accounted for much less variance than the PRI (Fig. 2). Positive exponential regressions between the GPP/PAR and the PRI were found also for each year in question. In order to reduce uncertainties associated with seasonal changes in incident radiation or the view zenith angle, we also tested the ability of the PRI product to estimate the GPP/PAR ratio for the summer months only (i.e. PAR >7 MJ m^{-2} day^{-1}). In a positive exponential regression, PRI still explained 45 % of the variance of GPP/PAR ($n=32$, $p< 0.0001$, RMSE = 0.1 g C MJ^{-1}). PRI was also a good estimator of RUE (GPP/APAR) ($n=23$; $r2=0.58$, $F=29.09$, $p<0.0001$) for 2001 in an evergreen needleleaf forest (Loobos, Netherlands, *Pinus sylvestris* stand) where we also test the ability of the PRI to estimate GPP/APAR following the same procedure described for Castelporziano holm oak forest.

The use of an exponential estimation of the RUE by means of the PRI for 2002 (RUE [g C MJ^{-1}] = 0.62 e $^{21.25 \times PRI}$; n=20; r^2=067; p<0.0001) together with PAR and NDVI strongly improved the MODIS NASA GPP estimate for 2001 (Fig. 3). The use of PRI significantly reduced the error in the estimate of the daily GPP measured in the flux tower when compared to the MODIS NASA GPP product (MODIS17) based on the fPAR product and the RUE estimate based on the maximum ecosystem RUE, the VPD, and the minimum temperature.

The up-scaling of the previous work at leaf and plant level (Gamon et al., 1995, Peñuelas et al., 1995, Peñuelas et al., 1997) to the 1 x 1 km pixel level was successful, despite a number of a priori expected problems. Unlike vegetation indexes, which are mainly related to the red-edge reflectance of the vegetation, the PRI has a very low signal. Nevertheless, despite this low signal and the coarse resolution of MODIS images, the PRI produced a very accurate signal of a leaf-level process, related to the dissipation of radiation excess by plants and consequent xanthophyll pigment epoxidation. It is also likely that PRI scales with seasonal pigment changes (e.g. carotenoids/chlorophyll a ratio) and other related photosynthetic processes with stronger signal (Filella et al., 2004, Sims and Gamon, 2002). A second possible problem relates to the temporal matching between data from the carbon flux and the satellite spectral data. The MODIS Terra platform passes over in the morning and thus may not capture the full day gas exchange performance. Furthermore, in spite of the high availability of remote sensing data provided by different satellites, there are still a number of problems regarding the use of this data, above all associated with computational difficulties when performing atmospheric corrections. Corrected reflectances from MODIS are available only for seven of its 36 bands, and the corrected data for constructing narrow-band spectral indexes such as the PRI are not available yet. Our data suggests that this problem can be overcome by working with spectral bands closely located in the green portion of the electromagnetic spectrum, such as those used in the PRI calculation, in order to make correction unnecessary. Therefore, this fact makes the data and the calculations available for everybody by accessing to MODIS data webpage. Previous work (Drolet et al., 2005) also provides evidence that atmospheric correction for close wavelengths is not necessary. A fourth issue is the consistent relationship between ground and satellite data that was found despite the fact that soil and plant respiration may produce a significant scatter in the relationship between PRI and carbon uptake. This is due to the fact that, while PRI tracks gross photosynthesis (i.e., direct carbon uptake not including respiratory loss), conventional flux sampling methods provide the net CO_2 flux (i.e., combined photosynthetic carbon gain and respiratory loss) from the sampling area and ecosystem respiration is estimated from environmental variables (temperature and water availability) and extrapolation of night-time values of ecosystem respiration into the daytime (Reichstein et al., 2005). Finally, there are also the confounding physical effects of canopy structure, leaf movement, sun angle, and soil background that may also significantly influence the PRI signal (Gamon et al., 1992). Areas with low vegetation cover would present problems when using this methodology (Filella et al., 2004, Sims et al., 2006a). An examination of a range of ecosystems reveals that the utility of the PRI will vary with the ecosystem in question due to contrasting environmental constraints, evolutionary strategies, and light-use efficiencies. A comprehension of ecophysiological principles will be needed to fully reveal these patterns and it is likely that new remote-sensing approaches incorporating PRI will contribute to this understanding.

In this study we provide evidence that a real time estimation of carbon uptake can be carried out at ecosystem, regional, and global levels on the basis of freely available remote sensing data that complements traditional well-established vegetation indices such as the NDVI with the PRI. Our results may thus be of great importance and have multiple applications such as the estimation of the productivity (CO_2 fixation) of any region or the detection of the effects of climatic change on vegetation that may occur before leaf-area reduction. But these results provide not only a significant technological improvement; they also provide an important conceptual advance since they show that optical signals incorporate information on vegetation physiological performance (photosynthetic rates linked to changes in pigment ratios) at an ecosystem scale. Our results warrant thus a generalized study of PRI performance in multiple ecosystems and conditions in order to confirm the high expectations raised by the results we present here.

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Figure legends

Figure 1. Seasonal course of daily biophysical variables for the evergreen forest in Castelporziano (2001-2002). A. Gross Primary Productivity (GPP; open circles) and Photosynthetic Active Radiation (PAR; black circles) derived from the eddy covariance tower, B. seasonal dynamics of vegetation indices: Normalized Difference Vegetation Index (NDVI; black squares) and Enhanced Vegetation Index (EVI; open squares), and C. GPP/APAR (black triangles) and Photochemical Reflectance Index (PRI; gray squares).

Figure 2. Relationships between daily GPP/PAR and the MODIS spectral indices. A. NDVI (p= 0.14, B. EVI ($p<0.0001$) and C. PRI ($p<0.0001$; $r^2=0.61$; GPP/PAR = 0.54 x $e^{26.83 \text{ x PRI}}$; F= 112.5903; n=51 RMSE= 0.159 g $C.MJ^{-1}$).

Figure 3. Relationships between the daily GPP estimated from eddy covariance data and from remote sensing. A. MODIS17 GPP derived from fPAR, climate data, and a RUE estimate based on the maximum ecosystem RUE, the VPD, and the minimum temperature, and B. GPP derived from the novel approach based on PAR, NDVI and PRI suggested here. The use of EVI instead of NDVI as an estimator of fPAR did not improve the GPP estimate (EVI GPP RMSE = 1.6 g C m^{-2} d^{-1} vs NDVI GPP RMSE = 1.1 g C m^{-2} d^{-1}). Black lines are the linear regression between datasets and dotted lines are the 1:1 relationships.

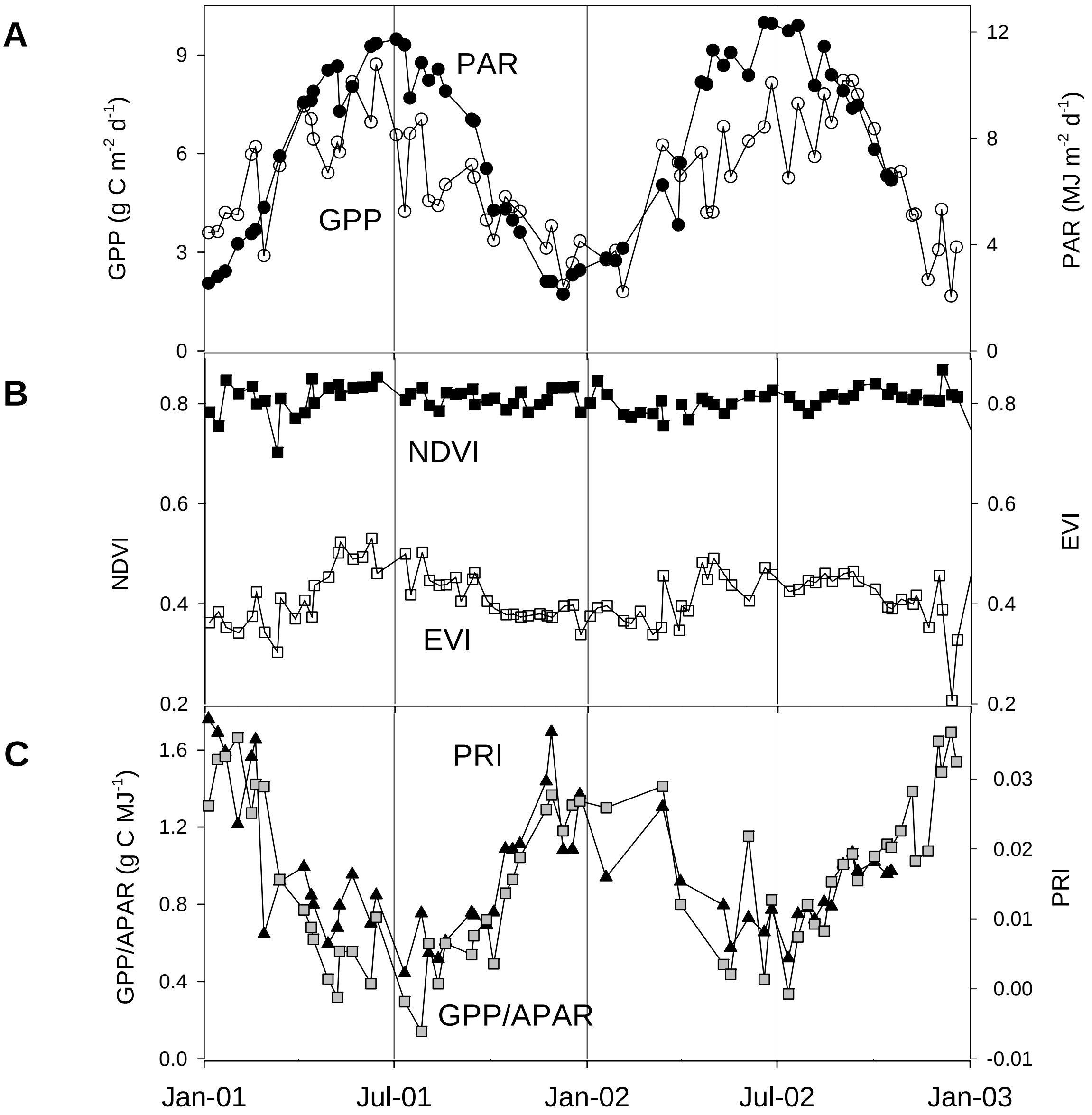
A
B
C
GPP (g C m^{-2} d^{-1})
PAR (MJ m^{-2} d^{-1})
PAR
GPP
0
3
6
9
0
4
8
12
NDVI
EVI
0.2
0.4
0.6
0.8
GPP/APAR (g C MJ^{-1})
PRI
GPP/APAR
0.0
0.4
0.8
1.2
1.6
-0.01
0.00
0.01
0.02
0.03
Jan-01
Jul-01
Jan-02
Jul-02
Jan-03

Figure 1.

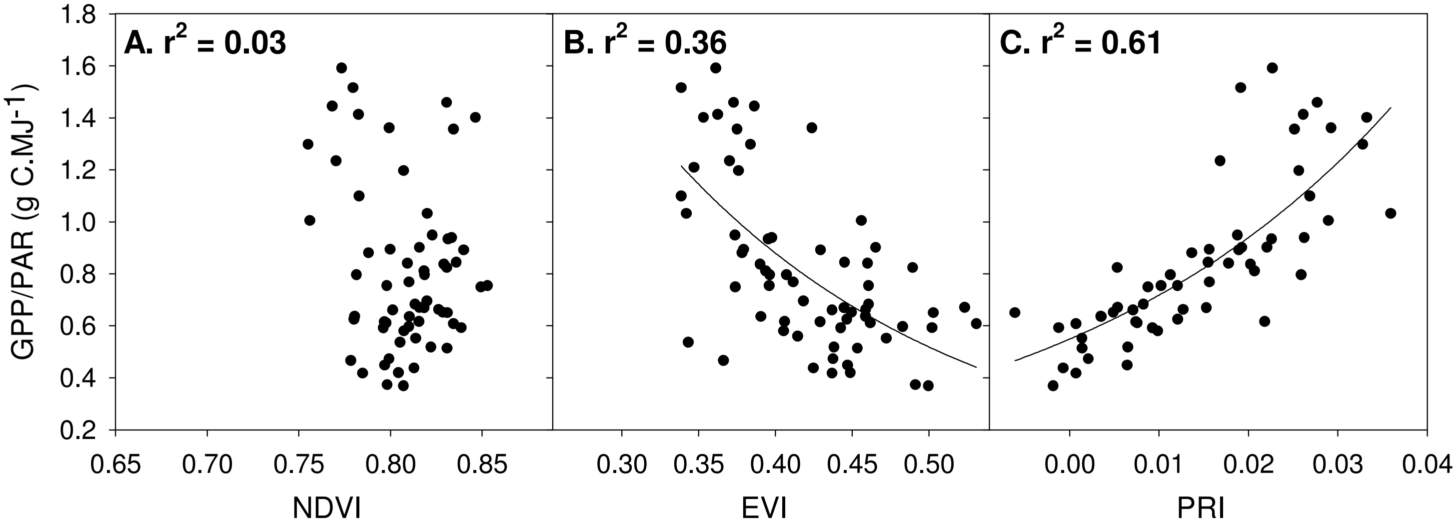
A. $r^2 = 0.03$
B. $r^2 = 0.36$
C. $r^2 = 0.61$
GPP/PAR (g C.MJ^{-1})
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.65
0.70
0.75
0.80
0.85
NDVI
0.30
0.35
0.40
0.45
0.50
EVI
0.00
0.01
0.02
0.03
0.04
PRI

Figure 2.

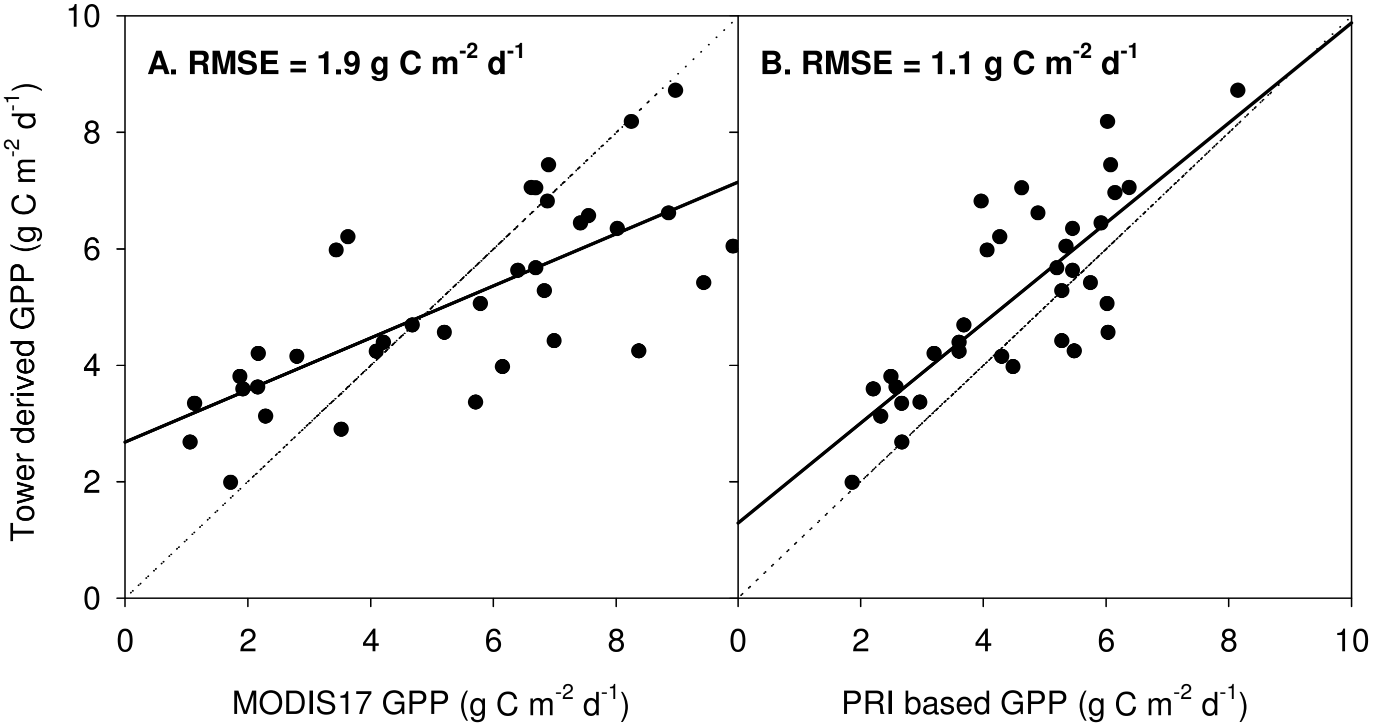
A. RMSE = 1.9 g C m-2 d-1
B. RMSE = 1.1 g C m-2 d-1
Tower derived GPP (g C m-2 d-1)
MODIS17 GPP (g C m-2 d-1)
PRI based GPP (g C m-2 d-1)
0
2
4
6
8
10

Figure 3.