The potential of the MERIS Terrestrial Chlorophyll Index for carbon flux estimation

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Abstract
In this study we evaluated the potential of the Medium Resolution Imaging Spectrometer (MERIS) Terrestrial Chlorophyll Index (MTCI) for monitoring gross primary productivity (GPP) across fifteen eddy covariance towers encompassing a wide variation in North American vegetation composition. The across-site relationship between MTCI and tower GPP was stronger than that between either the MODIS GPP or EVI and tower GPP, suggesting that data from the MERIS can be used as a valid alternative to MODIS for estimating carbon fluxes. Correlations between tower GPP and both vegetation indices (EVI and MTCI) were similar only for deciduous vegetation, indicating that physiologically driven spectral indices, such as the MTCI, may also be able to complement existing structurally-based indices in satellite-based carbon flux modeling efforts.

1. Introduction

Quantitative estimates of carbon dioxide exchange at regional to global scales are critical to improve our understanding of the links between carbon and climate. Tower-based eddy covariance (EC) techniques have been used across a wide range of ecosystems to provide information on seasonal and inter-annual carbon fluxes. However, flux tower sites only account for carbon fluxes within the designated tower footprint and the number and geographical distribution of towers across the globe is limited. Other attempts at estimating terrestrial carbon fluxes have concentrated on the development of process-based ecosystem exchange models (e.g. the Boreal Ecosystem Productivity Simulator (BEPS; Liu et al. 1997) and the Terrestrial Ecosystem Model (TEM; e.g. Raich et al. 1991)). Whilst such models show great promise, their applicability at regional and global scales is challenging due to their complexity and requirements for data that are often scarce or unavailable at the appropriate spatial and temporal scales. Carbon flux models that are driven by remotely sensed observations can be used to estimate gross primary productivity (GPP) frequently and over large areas; for example the NASA Carnegie-Ames-Stanford (NASA-CASA) model (Potter et al. 1993), the Terrestrial Uptake and Release of Carbon (TURC) model (Ruimy et al. 1996) and the Moderate Resolution Imaging Spectrometer Global Primary Productivity (MODIS-MOD17 GPP) model (Running et al. 2004)). The vast majority of satellite-based models are ‘Production Efficiency Models’ (PEMs) based on the light use (LUE) efficiency concept for conversion of absorbed photosynthetically active radiation (APAR) into biomass (Monteith 1977). In most PEMs the maximum LUE is empirically derived based on vegetation type and then reduced according to meteorological indicators of environmental stress. Thus whilst some PEM parameters can be estimated from satellite data, for example the fraction of absorbed photosynthetically active radiation (*f*PAR; Myneni et al., 2003; Prince & Goward 1995), the estimation of others, such as LUE, depend upon the availability of metrological data and vegetation maps. There can, however, be substantial errors in the estimation of GPP from satellite-based PEMs because of the coarseness of the metrological inputs commonly used to scale the LUE parameter and the quality and resolution of the landcover classification on which biome specific maximum LUE values are based (Heinsch et al., 2006; Zhao et al., 2006).

As a consequence of the difficulties involved with the parameterisation of both detailed process-based ecosystem exchange models and satellite-driven PEMs, there has been a renewed interest in developing productivity models that are entirely reliant upon satellite data, but which are not based upon the traditional LUE concept. Such models utilise vegetation indices to capture the seasonal dynamics of GPP (e.g. Rahman et al. 2005; Sims et al. 2008). The vast majority of these models are based on indices derived from NASA’s Moderate Resolution Imaging Spectrometer (MODIS; e.g. normalised difference vegetation index; NDVI and enhanced vegetation index; EVI), but with the continuity of MODIS still uncertain, there is clearly the motivation to extend the knowledge acquired from modeling efforts with the MODIS datasets to other sensors data, such as that from MERIS on board Envisat. Although MERIS was originally developed for ocean applications, its fine spectral resolution covering the visible and near infrared regions, radiometric accuracy (Curran and Steele 2005), moderate spatial resolution (300m and 1km), three-day repeat cycle, and assured continuity with the forthcoming launch of the Ocean and Land Colour Instrument (OLCI) onboard Sentinel 3, makes MERIS a potentially useful alternative for monitoring terrestrial vegetation.

In this study we explore the extent to which the Meris Terrestrial Chlorophyll Index (MTCI; Dash and Curran 2004) may be used as an alternative to MODIS-based vegetation indices, for estimating GPP across a range of vegetation types and climatic conditions. The MTCI appears a good candidate because the index contains information relating to canopy chlorophyll content, which is conceptually related to GPP through the dependence of the product of radiation absorbed by the canopy and LUE, on the presence of photosynthetic biomass, and thus chlorophyll content (Sellers et al. 1992). Several authors have previously reported significant correlations between the GPP of crops and chlorophyll-related indices (e.g. Gitelson et al. 2006; Wu et al. 2009), although these studies have primarily focused on the use of proximal (*in situ*) spectral sensors to develop such relationships. Furthermore, the potential of chlorophyll-related indices for GPP estimation has yet to be fully explored across a range of biomes. For evaluation purposes, we compared the MTCI results with those obtained from the more commonly used MODIS-derived EVI and MOD17 GPP products.

2. Sites, data and methods

We used carbon flux data from fifteen Ameriflux tower sites, representing considerable variation in region, climate and species composition (Table 1). Donaldson and Mize are both young slash pine forests in northern central Florida with long warm summers and mild winters. Blodgett is a young Ponderosa pine forest in the Sierra Nevada region of the western United States, which encounters moderate winters and relatively dry summers. The Niwot Ridge site is situated in the Rocky Mountains and is an example of a sub-alpine temperate coniferous forest with more extreme winters than the other evergreen forest sites. Harvard forest in Massachusetts and Bartlett forest in Maine are characteristic of the eastern deciduous forest of the United States with cold winter climates. In contrast both the Missouri Ozark and Willow Creek sites have warm summers. Mature sugar maple, aspen and yellow birch are dominant at Willow Creek whereas Oak hickory is dominant at the Missouri site. The Lost Creek site in Northern Wisconsin is representative of a mixed forest/deciduous shrubland whereas the Walnut River, Vaira Ranch and Fort Peck sites are representative of grasslands found across a wide geographic and climatic gradient. Finally, Bondville and the two Mead sites are taken as representative of corn and soybean croplands.

2.1. MERIS and MODIS spectral data

The 1km spatial resolution MERIS MTCI data were obtained from the UK Natural Environment Research Council Earth Observation Data Centre (NERC NEODC; http://www.neodc.rl.ac.uk) as 8-day composites. MTCI data were composited from standard European Space Agency (ESA) Level 2 (geophysical) products using an arithmetic mean. We selected data where the MTCI value was equal or greater than one to remove erroneous values not related to vegetation cover. Flux tower footprints are generally less than 1 km (Schmid, 2002), however, it can be difficult to precisely locate which pixel the footprint falls within. Consequently, we extracted both the central pixel and the mean of the central 3 x 3 km area thought to be centred on the flux tower to determine which provided the best correlation with GPP.

Both the 16-day composite MODIS EVI (MOD13) and 8-day composite MOD17 GPP (Collection 5 datasets) were acquired from the Oak Ridge National Laboratory’s Distributed Active Archive Centre (DAAC) (http://www.modis.ornl.gov/modis/index.cfm). We used the MODIS quality control flags to select data with low cloud cover and listed as “Good Quality”. The MOD17 GPP product is a PEM model where GPP is modelled for each biome as a function of quantum yield and LUE, constrained by coarse resolution temperature data and measures of vegetation moisture status (Heinsch et al. 2003). We used the average EVI and MOD17 GPP values of a 3 x 3 km area surrounding the flux towers to compare with the tower flux data. Furthermore, to make valid comparisons between the MTCI, EVI and MODIS GPP results, we averaged two consecutive periods of the MTCI and MOD17 GPP 8-day composites, to conform to the 16-day period of the EVI data.

2.2 Tower-based Carbon Flux Data

Eddy covariance techniques were used to measure carbon fluxes at each site (see Table 1 for methods references). On all occasions we used level 4 marginal distribution sampling gap filled measurements of GPP obtained from the Ameriflux website (http://public.ornl.gov/ameriflux/dataproducts.shtml) to calculate 16-day averages. We only used data collected during the growing season. This period was determined by smoothing the MTCI data using an inverse discrete Fourier transformation and finding the point of inflexion from the smoothed data. Estimation of the growing season duration was confirmed by visually interpreting each time series curve. Furthermore, to facilitate comparisons between tower-measured GPP and the MTCI, EVI and MODIS GPP datasets, we used only those dates where data were available for all four variables (i.e. a total of 554 complete datasets).

2.3 Statistical analysis

Time series and scatterplots were used to visually examine relationships between the remotely sensed datasets and measures of tower GPP within individual sites, within a single land cover type and across different land covers. Pearson’s product moment correlation coefficient and Spearman’s rank correlation coefficient were used to examine the nature (positive or negative) and significance of theses relationships. Both Pearson’s and Spearman’s correlation coefficients and significance values were similar for the relationships examined; Pearson’s correlation coefficients are provided in the text and figures. Correlations with p values < 0.05 were considered significant.

3. Results

There was good agreement between annual tower GPP dynamics and the MTCI for most of the sites during the active photosynthetic period. Figure 1 shows an example of a seasonal profile from four of the sites analysed, one from each land cover type. For the deciduous sites seasonal increases and decreases in tower GPP were closely tracked by the MTCI. At Willow Creek the seasonal GPP pattern corresponded well with variation in both the MTCI and EVI, although a time lag was apparent in the EVI data as tower GPP began to decrease in late July (Fig. 1). Similar patterns were observed for the other deciduous sites (*data not shown*). Change in tower GPP over the growing season was significantly less in the evergreen forests and grasslands, compared to the deciduous sites. Despite this, there were clear seasonal trends in tower GPP, which were not tracked particularly well by either vegetation index at the evergreen sites. At Niwot Ridge, small increases in both indices were observed during the growing season although the large increase in tower GPP during May was not captured by either index (Fig. 1). The inability of the MTCI and EVI to effectively capture the seasonal pattern in tower GPP was also observed for most of the other evergreen forest sites in this study (*data not shown*). In comparison to the evergreen forests, the correspondence between both vegetation indices and tower GPP was closer for all grassland sites. All grasslands showed increases in both vegetation indices that corresponded to increases in tower GPP (Fig. 2). However, for all satellite-based products the correspondence with tower GPP was closer at the Walnut River site than at the other grasslands sites (Fig. 1 and Fig 2.). Both vegetation indices were also able to track summer increases in GPP at the cropland sites, although the highest index values recorded throughout the season did not always correspond to the highest measures of tower GPP. For example at the Bondville site tower GPP peaksedn mid-late June, whereas the maximum MTCI value was recorded approximately 1 month later (based on the 16-day composites used in this study). The EVI also exhibited a similar pattern to MTCI although the lag between maximum GPP and maximum growing season EVI was greater (Fig. 1). In addition, both indices increased steadily during the early part of the growing season (March – May) when tower GPP was low but stable. Similar patterns were observed across all cropland sites (*data not shown*). The MODIS GPP product captured the seasonal patterns at most sites, with the exception of Blodgett, although tower GPP was significantly underestimated at a large number of sites (Fig 1. and Fig 2.).

The scatter plots and the Pearson's correlation coefficient (r) revealed that the MTCI was positively correlated with tower GPP and MTCI for all sites indicating a generally good correspondence between increases in MTCI and increases in tower GPP (Fig. 2 and Table 2). Use of the MTCI from the 1 km pixel centred on the flux tower location as opposed to the 3 x 3 km mean, had little effect on the correlation between MTCI and tower GPP for all sites except Mize, where the correlation for the 3 x 3 km data was substantially higher (Table 2). Previous studies using a number of the same flux tower sites have reported slightly higher correlations between tower GPP and MODIS derived products (i.e. EVI and MODIS GPP) for the 3 x 3 km means surrounding the tower (e.g. Sims et al. 2006), thus for comparison purposes we used the 3 x 3 km mean MTCI, MODIS GPP and EVI for the rest of our analysis. Out of the 20 correlations computed between the MTCI and GPP, 15 were statistically significant, although the strength of the correlations varied between and sometimes within land cover types.

The correlation between MTCI and tower GPP was strongest for the deciduous forests, both within and across sites (Table 2; Fig. 2). The MODIS GPP product and the EVI were also strongly correlated with tower GPP for the deciduous forests although the MODIS GPP product overestimated tower GPP at most of the sites (points falling above the 1 to 1 line in Fig. 2). In comparison to the deciduous forests, the strength of the correlations between all the satellite derived measures and tower GPP was relatively weak across most of the evergreen forests (Table 2; Figure 1). Only the Mize site showed significant correlations between MTCI and tower GPP ($r = 0.645$, $p = 0.005$), however this relationship was not significant when tower GPP was correlated with the MTCI values of the single pixel centred upon the flux tower (Table 2). The difference in the strength of the relationship is likely to be related to the heterogeneity of the land cover surrounding the flux tower at Mize. Whereas evergreen forest is the predominant land cover at the 1 km scale, the increase in the spatial extent of the MTCI footprint to 3 x 3 km may have resulted in the inclusion of deciduous vegetation, producing a stronger correlation between MTCI and tower GPP at this scale (http://daac.ornl.gov/MODIS/). The correlations between tower GPP and the EVI for the evergreen sites were statistically significant, but generally weak. As for the MTCI, the Mize site showed the strongest correlation between EVI and tower GPP (Table 2; Fig.2). However, there was a difference in the pattern of the correlation between the two indices and tower GPP for the Blodgett site. Here, MTCI values were higher than those observed at any of the other evergreen sites for the same value of tower GPP, whereas this pattern was not visible in the EVI data where EVI values were similar for a given tower GPP for all evergreen sites (Fig. 2). The higher MTCI values recorded at Blodgett may reflect a higher concentration of chlorophyll in the leaves of these trees, which is indicative of young forests such as Blodgett (Table 1), although further work is required to confirm the actual cause and effect. The MODIS GPP product was also weakly correlated with tower GPP at the Blodgett site but was more strongly correlated with tower GPP for the remaining evergreen sites than either of the vegetation indices. More work is needed to identify the exact reasons for the lack of variation in MTCI for a number of the evergreen forests but reasons could include shadowing effects caused by the conical canopy structure and density of the evergreen needleleaf trees, the inability of the MTCI to detect the small changes in seasonal chlorophyll content characteristic of needleaf species (e.g. Lewandowska and Jarvis 1977; Khan et al. 2000) and/or stress induced declines in photosynthetic efficiency, which are not accompanied by changes in chlorophyll content (e.g. Bourdeau 1959; Gamon et al. 1995).

At the grassland sites, MTCI was significantly correlated with tower GPP both for individual sites and across all grassland sites, but the strength of the correlation across sites was weaker than that observed across the deciduous forests ($r = 0.648$, $p<0.001$ and $r = 0.785$, $p<0.001$; respectively; Table 2). All remotely sensed products were more strongly correlated with tower GPP at Walnut River than at the other grasslands. The range of MTCI values was also greatest at Walnut River despite similar recorded values of tower GPP (Fig. 2; Table 2). We propose that these observed differences are related to differences in species composition between the grassland sites. Grasslands are naturally vertically and horizontally heterogeneous. For example, Vaira ranch is a grazed grassland opening in a region of oak/grass woodland dominated by C3 plants, whereas the Walnut River grassland site is dominated by tall prairie grasses and contains a mixture of C3 and C4 species (http://www.modis.ornl.gov/modis/index.cfm). Results from a recent study aimed at mapping C3 and C4 grassland species using the MTCI, suggest that C4 grasslands exhibit higher MTCI values during the peak growing season compared to those dominated by C3 species (Foody and Dash 2007), which could explain the higher MTCI values observed at the Walnut River site.

Of all satellite derived products, MTCI showed the strongest correlations with tower GPP for the cropland sites (Table 2), although there was a significant amount of scatter within these relationships (Fig. 2). The large amount of scatter at low levels of tower GPP is primarily a function of increasing values of MTCI when GPP is low and stable (Fig. 1). Although further research is needed to elucidate the exact cause of these variations, one possible reason for this may be related to how the active period of photosynthesis was determined. Although the MTCI begins to increase towards the end of January, Soybean and Corn seeds are often not sown until the spring time. Consequently, the low tower GPP values and increasing MTCI values which were observed during the first 2 -3 months of the year may be representative of fallow land, either gradually being colonised by weed species or subject to a change in moisture regime, as opposed to actual crop growth. This may also explain why the seasonal profiles of MCTI do not show similar variations in MTCI when GPP is low and stable towards the end of the active period of photosynthesis (Fig. 1) but rather an abrupt decrease, which may be indicative of crop harvest and a return to fallow land. Although the correlation coefficients were also strong between cropland tower GPP and the MODIS GPP product, the product consistently and significantly underestimated tower GPP for these sites (Table 2, Fig. 2). The strong correlation observed between MTCI and GPP at the cropland sites is particularly encouraging since our findings are consistent with those of Wu et al. (2009). Gitelson et al. (2006) also reported similar correlations between chlorophyll related indices, and estimates of GPP at the same two Mead sites used in this study. The chlorophyll indices were derived from the same spectral region as MTCI, but measures were derived at a much higher spatial and spectral resolution using *in situ* sensors.

This study is the first to investigate the relationships between MTCI and GPP within and across a range of land covers and vegetation types. Our results indicate that even though the MTCI and EVI show similar correlations with GPP for some vegetation types (e.g. decidous) the indices are actually depicting different, but sometimes related, attributes of the vegetation. Differences between the two indices were clearly apparent in the time series profiles where a greater lag was observed between the onset of the end of season reduction in GPP and down turn in the EVI, and also in the scatter plots where relationships between MTCI and GPP differed somewhat to that of the EVI. Because the EVI is a measure of vegetation structure and greenness, whereas the MTCI is relatively insensitive to vegetation configuration, similar relationships were observed between GPP and both vegetation indices when canopy greenness and structure were correlated in time (e.g. in deciduous vegetation), but differences were apparent when seasonality in the temporal profile of the indices was weak (e.g. grasslands, agricultural sites and evergreen forests).

Because GPP is not solely a function of chlorophyll content, there were clear differences in the MTCI-tower GPP relationship amongst land cover types and sometimes within, thus the use of MTCI as a single variable to predict GPP is evidently not feasible for sites that are not dominated by deciduous vegetation that has a predictable seasonal cycle. To a large extent the same is true for the EVI derived from MODIS data. The correlation between GPP and MTCI was however, stronger than the correlations between GPP and the other satellite derived products tested, when data from all sites were combined ($r = 0.780$ $p < 0.001$, Table 2). Thus there is evidently the potential for MTCI to be used as an alternative to EVI in GPP modelling efforts. Clearly for the accurate estimation of GPP, any MTCI-based model must include variables that are able to account for stress induced changes in photosynthetic efficiency. Sims et al. (2008) found that adding a temperature component to their EVI model improved GPP estimations for both deciduous and evergreen sites. What effect the addition of a temperature or radiation component will have on a MTCI-based model, given the differences observed in the relationships between tower GPP and both spectral indices for certain land covers, requires further investigation. However, if as suggested, chlorophyll content is the most relevant community property for predicting vegetation productivity (Whittaker and Marks 1975; Dawson et al. 2003), then a GPP model based on physiologically driven spectral indices such as MTCI, should be complementary to existing satellite-driven models, which estimate GPP from primarily structurally driven spectral indices such as the EVI. Further research should also be directed towards understanding the effect of compositing period on the relationship between GPP and MTCI. In this study we conformed to the 16-day compositing period of the standard MODIS EVI product for comparison purposes, even though the MTCI is routinely available as an 8-day composite product. Further research efforts should also focus on the effect of variable pixel size on MTCI-GPP relationships, specifically in heterogeneous locations. We found that the correlations between MTCI and tower GPP over a 1 x 1 km and 3 x 3 km area were consistent for all but one of the sites studied, indicating a degree of homogeneity in the seasonal responses of vegetation at both these scales. However, we did not account for the heterogeneity that may exist at the sub kilometre scale and of any temporal and spatial variations in flux tower footprints that may be present between and within sites. From a technical perspective, further work should also be focused on the potential benefits of more rigorous pre-processing procedures to derive the standard 8-day composite MTCI data. Currently only a relatively simple atmospheric correction is applied to the data (i.e. correction for Rayleigh scattering, water vapour and ozone absorption) and no correction is made for the influence of directional effects (although preliminary investigations suggest that MTCI is minimally affected by change in view angle). Consequently, it is expected that additional pre-processing and an improved atmospheric correction, that is one which includes a correction for aerosol loading and cloud shadowing, could further improve the strength of the correlations between MTCI and GPP.

4. Conclusion

Carbon flux models that rely solely on remote sensing data have shown promise for estimating GPP across a variety of land cover types. However, these models are commonly derived from predominantly structurally driven spectral indices and most are obtained from the MODIS sensor. With the continuity of MODIS uncertain and data from other high temporal, spatial and spectral resolution sensors becoming more widely available it is worthwhile exploring alternative methods of estimating GPP using remote sensing products. In this study, we have shown that correlations between the physiologically driven MTCI derived from the MERIS sensor, and GPP were often as strong and sometimes stronger than those between GPP and both the MODIS derived EVI and GPP product across a range of different land cover types and climatic conditions. Therefore the MTCI appears to be a viable alternative to EVI for inclusion in carbon modelling efforts. Correlations between tower GPP and the MTCI and EVI were similar for many of the deciduous and grassland sites, although different relationships emerged between the two indices and tower GPP for evergreen and cropland sites, probably due to the decoupling of structural and physiological properties of the vegetation. Consequently, per pixel models based on physiological spectral indices such as the MTCI may also complement existing models driven by structural information. Work is ongoing to fully explore whether improvements in the MTCI atmospheric correction procedure and the inclusion of environmental physiological variables will aid in the development of a robust model of GPP using MERIS data.

Acknowledgements

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Figure Caption

Fig. 1. Time series of the MERIS Terrestrial Chlorophyll Index (MTCI), MODIS GPP product and MODIS-Enhanced Vegetation Index (EVI) for selected sites representing each land cover type. Data are means (± standard error) for each composite period with a complete dataset, for the active period of photosynthesis, across all years used in this study.

Fig. 2. Gross primary production measured at the flux towers (tower GPP) as a function of the MERIS Terrestrial Chlorophyll Index (MTCI), MODIS GPP product and MODIS-Enhanced Vegetation Index (EVI) for each of the sites dominated by deciduous forests, evergreen forests, grasslands and croplands. Data are means (± standard error) for each composite period with a complete dataset, across all years used in this study.

Tables

Table 1. Vegetation type, location and other characteristics of the fifteen eddy covariance flux tower sites used in this study.

Site name	Vegetation type	Latitude/Longitude(?)	Stand age (years)	Years	Methods references
Forest					
Blodgett	Evergreen needleleaf forest	38.8953, -120.6328	7-8	2003-2005	Goldstein et al. 2000
Niwot Ridge	Evergreen needleleaf forest	40.0329, -105.5464	100	2003-2005	Monson et al. 2002
Donaldson	Evergreen needleleaf forest	29.7548, -82.1633	11-13	2003-2004	Gholz and Clark 2002
Mize	Evergreen needleleaf forest	29.7648, -82.2448	11	2003-2004	
Harvard Forest	Deciduous broadleaf forest	42.5378, -72.1715		2003-2005	Urbanski et al. 2007
Bartlett	Deciduous broadleaf forest	44.0646, -71.2881	99	2004-2006	Jenkins et al. 2007
Missouri Ozark	Deciduous broadleaf forest	38.7441, -92.2000	>150	2004-2006	
Willow Creek	Deciduous broadleaf forest	45.9059, -90.0799	60-80	2003-2005	Bolstad et al. 2004
Lost Creek	Mixed forest/shrubland	46.0827, -89.9792		2003-2005	Davis et al. 2003
Non-forest					
Walnut River	Grassland	37.5208, -96.8550		2003-2004	Song et al. 2005
Vaira Ranch	Grassland	38.4067, -120.9507		2003-2006	Baldocchi et al. 2004
Fort Peck	Grassland	48.3079, -105.1005		2005-2006	
Bondville	Cropland	40.0061, -88.2919		2003-2006	Meyers and Hollinger 2004
Mead Rainfed	Cropland	41.1797,		2003-2006	Suyker et al.

		-96.4396			2004
Mead	Cropland	41.1649,		2003-2005	Suyker et al.
Rotation		-96.4701			2004

Table 2. Pearson's product moment correlation coefficients (r values) calculated between Eddy Covariance tower measurements of gross primary productivity (GPP) and the MERIS Terrestrial Chlorophyll Index (MTCI), the MODIS Gross Primary Productivity (MODIS GPP) and the Enhanced Vegetation Index (EVI) products.[a]

	No. samples	MTCI 1 pix Versus Tower GPP		MTCI 3x3 Versus Tower GPP		MODIS GPP 3 Tower GPP			
		r	***p***	**r**	***p***	**r**	***p***	**r**	***p***
Willow Creek	32	0.942	<0.001	0.945	<0.001	0.913	<0.001	0.944	<0.001
Harvard Forest	36	0.917	<0.001	0.925	<0.001	0.810	<0.001	0.889	<0.001
Lost Creek	24	0.837	<0.001	0.828	<0.001	0.887	<0.001	0.887	<0.001
Bartlett	37	0.862	<0.001	0.871	<0.001	0.882	<0.001	0.967	<0.001
Missouri Ozark	51	0.869	<0.001	0.868	<0.001	0.901	<0.001	0.902	<0.001
Blodgett	51	0.259	ns	0.243	ns	0.311	0.026	0.283	0.045
Niwot Ridge	37	0.298	ns	0.297	ns	0.729	<0.001	0.348	0.035
Donaldson	27	0.167	ns	0.187	ns	0.521	0.005	0.228	ns
Mize	17	0.521	ns	0.645	0.005	0.530	0.028	0.686	0.002
Walnut River	23	0.974	<0.001	0.969	<0.001	0.977	<0.001	0.847	<0.001
Vaira Ranch	42	0.612	<0.001	0.628	<0.001	0.648	<0.001	0.744	<0.001
Fort Peck	29	0.583	<0.001	0.575	0.001	0.766	<0.001	0.764	<0.001
Bondville	57	0.901	<0.001	0.894	<0.001	0.908	<0.001	0.656	<0.001
Mead Rainfed	56	0.822	<0.001	0.828	<0.001	0.837	<0.001	0.627	<0.001
Mead Rotation	35	0.822	<0.001	0.797	<0.001	0.760	<0.001	0.713	<0.001
Deciduous Forest	180	0.874	<0.001	0.875	<0.001	0.812	<0.001	0.908	<0.001
Evergreen Forest	132	0.319	ns	0.265	0.002	0.616	<0.001	0.567	<0.001
Grassland	94	0.650	<0.001	0.648	<0.001	0.680	<0.001	0.636	<0.001
Cropland	148	0.822	<0.001	0.820	<0.001	0.825	<0.001	0.627	<0.001
All sites	554	0.787	<0.001	0.780	<0.001	0.606	<0.001	0.709	<0.001

[a] MTCI in the first column is based on the central 1 km pixel most closely overlapping the tower footprint. The rest of the columns represent the mean for the 3 x 3 km area centred on the tower. All relationships were based on the individual data points from the photosynthetically active period (i.e. excluding winter); ns = not significant ($p > 0.05$).