Sensitivity of Near Real-time MODIS Gross Primary Productivity in Terrestrial Forests Based on Eddy Covariance Measurements

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Abstract: As an important product of Moderate Resolution Imaging Spectroradiometer (MODIS), MOD17A2 provides dramatic improvements in our ability to accurately and continuously monitor global terrestrial primary production, which is also significant in effort to advance scientific research and eco-environmental management. Over the past decades, forests have moderated climate change by sequestrating about one-quarter of the carbon emitted by human activities through fossil fuels burning and land use/land cover change. Thus, the carbon uptake by forests reduces the rate at which carbon accumulates in the atmosphere. However, the sensitivity of near real-time MODIS gross primary productivity (GPP) product is directly constrained by uncertainties in the modeling process, especially in complicated forest ecosystems. Although there have been plenty of studies to verify MODIS GPP with ground-based measurements using the eddy covariance (EC) technique, few have comprehensively validated the performance of MODIS estimates (Collection 5) across diverse forest types. Therefore, the present study examined the degree of correspondence between MODIS-derived GPP and EC-measured GPP at seasonal and interannual time scales for the main forest ecosystems, including evergreen broadleaf forest (EBF), evergreen needleleaf forest (ENF), deciduous broadleaf forest (DBF), and mixed forest (MF) relying on 16 flux towers with a total of 68 site-year datasets. Overall, site-specific evaluation of multi-year mean annual GPP estimates indicates that the current MOD17A2 product works highly effectively for MF and DBF, moderately effectively for ENF, and ineffectively for EBF. Except for tropical forest, MODIS estimates could capture the broad trends of GPP at 8-day time scale for all other sites surveyed. On the annual time scale, the best performance was observed in MF, followed by ENF, DBF, and EBF. Trend analyses also revealed the poor performance of MODIS GPP product in EBF and DBF. Thus, improvements in the sensitivity of MOD17A2 to forest productivity require continued efforts.

Keywords: MOD17A2; FLUXNET community; eddy covariance (EC); gross primary productivity (GPP); forest ecosystem; evaluation

1 Introduction

Forest productivity act as the largest and most important component of the global carbon cycles by linking terrestrial biosphere and the atmosphere (Zhao *et al*., 2006; Beer *et al*., 2010; Tang *et al*., 2012). This is because they quantify the transformation of light energy to terrestrial CO_2 assimilation through photosynthesis. Our understanding of forest productivity and its response to climate variability is critical to evaluate ecosystem vul-

nerability and adaptation potentials (Zhao and Running, 2010; Sjöström *et al.*, 2013; Pan *et al.*, 2014), particularly in the context of changing global environments. Terrestrial gross primary productivity (GPP) also contributes significantly to human welfare through provision of food, fiber, and wood.

Since 2000, NASA′s Moderate Resolution Imaging Spectroradiometer (MODIS) has been providing repeated and consistent observations of terrestrial GPP estimates across broad spatio-temporal scales, and has advanced tremendously over the past decade. The major approaches used to monitor variability in GPP include light-use efficiency models (Running *et al.*, 2004; Coops *et al.*, 2007), ecosystem process models (Morales *et al.*, 2005; Nightingale *et al.*, 2007), empirical models that use remotely-sensed data calibrated against in situ eddy covariance (EC) measurements (Rahman *et al.*, 2005; Wu *et al.*, 2010; 2011), and machine-learning algorithms (Yang *et al.*, 2007; Xiao *et al.*, 2010). However, validations of these models are usually based on a relatively small dataset, and examination on both spatial and temporal variations in remotely sensed proxies and modeled estimates with tower-based GPP are still limited (Verma *et al.*, 2014).

Evaluation of ecosystem-level vegetation production is a key research in global climate change field. The MOD17A2 product has been improved from collection 4.5 (C4.5) to collection 5 (C5) in consideration of problems associated with its algorithm and upstream input data (Zhao *et al.*, 2006; Chasmer *et al.*, 2009). Ultimately, the effectiveness and value of such dataset is determined by the capacity to quantify and explain site-level measurements of plant functional characteristics. To meet this end, a global ground-based monitoring network of micrometeorological tower sites (FLUXNET) has been established that use eddy covariance technique to estimate site-level GPP as the sum of net ecosystem production (NEP) and ecosystem respiration (Coops *et al.*, 2007). Now the FLUXNET community throughout the world has been operated for several decades and enabled scientists to assess satellite-based GPP at different time scales across diverse terrestrial ecosystems encompassing forest, grassland, cropland, and desert (Verma *et al.*, 2014). However, evaluating differences between modeled and measured GPP is a challenging task owing to large variations in climate conditions, soil types and vegetation characteristics, as well as scale mismatch with satellite data.

Although plenty of studies have verified the capacity of MODIS GPP with ground-based measurements covering a wide range of biome types and proposed useful information to reduce uncertainties (Wang *et al.*, 2013; Pan *et al.*, 2014), evaluations of MODIS GPP (C5) remain limited to this day. Sjöström *et al.* (2013) found that this product underestimated GPP across several flux sites, most significantly in the dry areas. In addition, forests cover approximately 30% of the Earth′s total land area and account for 75% of the terrestrial GPP with a great number of forest types. Previous studies usually focus on a single site or individual forest type (Coops *et al.*, 2007; Propastin *et al.*, 2012), but few have comprehensively validated the performance of MODIS GPP estimates for diverse forest types. Therefore, the primary objectives of this study are: 1) to determine how the near real-time MODIS-derived GPP (C5) performs at the seasonal to interannual time scales in forest ecosystems including evergreen broadleaf forest (EBF), evergreen needleleaf forest (ENF), deciduous broadleaf forest (DBF), and mixed forest (MF); and 2) to evaluate how well the MODIS GPP product captures the interannual trends of the main forest types.

2 Methods and Materials

2.1 FLUXNET data

The analyses performed in this study are based on weekly data from 16 flux towers, giving a total of 68 site-year datasets across different forest types including EBF, ENF, DBF and MF. These flux sites also represent considerable variations in geographical location, microclimate condition, stand age, and species composition. The site descriptions of all towers including site name, latitude/longitude, tree age, maximum leaf area index (LAI), years of data used, and references are summarized in Table 1. Most of these forests are temperate and boreal with diverse species composition encompassing hardwoods, conifers and mixed woods with dissimilar soils, hydrological patterns and stand ages. Two tropical rain forest sites (TRF) situated near the equator are also included. Forests in the mid- and high latitudes of northern hemisphere are considered as an important storage of atmospheric CO_2, which may help understand the ′missing carbon sink′ of Earth (Houghton *et al.*, 1999). Furthermore, only a small amount of scientific data and

Table 1 FLUXNET sites used in this study

Site code	Longitude	Latitude	Forest type	LAI	Age	Year used	Reference
Br-Sa1	54.96°W	2.86°S	Evergreen broadleaf forest	5.3	Old-growth	2002–2004	Grant *et al.*, 2009
JP-PSO	102.30°E	2.97°N	Evergreen broadleaf forest	6.5	–	2004–2006	Saigusa *et al.*, 2008
US-KS2	80.67°W	28.61°N	Evergreen broadleaf forest	2.1	16	2004–2006	Seiler *et al.*, 2009
IT-Cpz	12.38°E	41.71°N	Evergreen broadleaf forest	3.5	38	2001–2008	Garbulsky *et al.*, 2008
ES-ES1	0.32°W	39.35°N	Evergreen needleleaf forest	2.6	~100	2004–2006	Reichstein *et al.*, 2005
FR-LBr	0.77°W	44.72°N	Evergreen needleleaf forest	4.8	44	2006–2008	Berbigier *et al.*, 2001
US-Ho1	68.74°W	45.21°N	Evergreen needleleaf forest	5.6	109	2002–2004	Richardson *et al.*, 2012
DE-Tha	13.57°E	50.96°N	Evergreen needleleaf forest	4.8	120	2001–2008	Grünwald and Bernhofer, 2007
US-MMS	86.41°W	39.32°N	Deciduous broadleaf forest	4.1	70	2004–2006	Dragoni *et al.*, 2011
US-Ha1	72.17°W	42.54°N	Deciduous broadleaf forest	4.7	75–110	2004–2006	Blonquist *et al.*, 2010
DE-Hai	10.45°E	51.08°N	Deciduous broadleaf forest	4.8	~250	2004–2006	Knohl *et al.*, 2003
FR-Hes	7.07°E	48.67°N	Deciduous broadleaf forest	5.7	35	2001–2008	Granier *et al.*, 2002
IT-Non	11.09°E	44.69°N	Mixed forest	1.8	15	2006–2008	Carvalhais *et al.*, 2010
US-Syv	89.35°W	46.24°N	Mixed forest	4.1	Old-growth	2002, 2005, 2006	Desai, 2010
DE-Meh	10.66°E	51.28°N	Mixed forest	–	~4	2004–2006	Don *et al.*, 2009
BE-Vie	5.99°E	50.31°N	Mixed forest	5.1	120	2001–2008	Aubinet *et al.*, 2002

Note: '–' means no data. LAI is leaf area index

literature exist in Africa compared with those in North America, Europe and Asia owing to sparse and limited EC sites and long-term ecological research stations (Williams *et al.*, 2008; Sjöström *et al.*, 2013). It unfortunately leads to a poor understanding of vegetation productivity and its responses to climate variability in African ecosystems. Thus, this study systematically validated the performance of MODIS GPP with EC-measured GPP at the seasonal and interannual time scales for the major forest types on Earth.

Flux towers are designed with standard measurement protocols, data quality control and storage systems to form a global network called FLUXNET, which reduces the uncertainty associated with site-to-site variations in flux observations and makes comparisons among sites (Beer *et al.*, 2010). The level 4 product provides measurements of canopy-scale water vapor flux, CO_2 flux, meteorological variables and estimates of GPP as the residual of measured net ecosystem carbon exchange (NEE) and modeled ecosystem respiration using an empirical temperature response function (Reichstein *et al.*, 2005). The temperature response function is calibrated using nighttime data when winds are usually low and assumes that the calibrated relationship holds during daytime (Lloyd and Taylor, 1994). NEE is gap-filled using the artificial neural network (ANN) method or the marginal distribution sampling (MDS) method (Papale

and Valentini, 2003). In this study, we used the standardized GPP data calculated from NEE gap-filled using the MDS approach. For each flux site, at least three years′ data were obtained to reduce uncertainties associated with year-to-year variation. In addition, up to eight years of data on typical flux sites of the main forest types were used for long-term trend analyses.

2.2 MODIS product

The verification exercise is based on collection 5 (C5) MODIS GPP data, which are available at the Oak Ridge National Laboratory′s Distributed Active Archive Center website (http://www.modis.ornl.gov/modis/index.cfm). Daily MODIS GPP is calculated according to the following algorithm:

$$GPP = \varepsilon_{max} \times 0.45 \times SW_{rad} \times FPAR \times fVPD \times fT_{min} \quad (1)$$

where ε_{max} is the maximum light use efficiency; SW_{rad} is the short-wave downward solar radiation, of which 45% is photosynthetically active radiation (PAR); *FPAR* is the fraction of PAR absorbed by plants; and *fVPD* and fT_{min} are the reduction scalars from water stresses and low temperature, respectively. The MODIS GPP C5 product used in this study implements 6-hourly National Center for Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis 2 data, including daily minimum temperature (T_{min}), daytime temperature (T_{day}),

daily average temperature (T_{avg}), daily vapor pressure, and daily total SW_{rad}. NCEP/DOE 2 is capable of capturing major changes in the surface climate anomalies (Betts *et al.*, 2006). FPAR in the algorithm is derived from the 8-day MOD15A2 1 km product. To map biome-specific physiological parameters (ε_{max}, minimum and maximum temperatures, and vapor pressure saturation deficit (VPD)) using a Biome Properties Look-Up Table (BPLUT), the 1 km University of Maryland (UMD) land cover classification scheme in the MOD12Q1 product was used. Data from an area of 3 km × 3 km MODIS GPP cells centered at each flux site were analyzed to represent the tower footprint. Extracting a 3 × 3 window for comparison with site data prevents potential errors in georectification of the satellite data. For a detailed discussion of issues related to georectification when comparing site data with satellite products see Heinsch *et al.* (2006) and Propastin *et al.* (2012).

3 Results

3.1 Site-specific evaluation of multi-year mean annual MODIS GPP product

Figure 1 illustrates the multi-year mean annual MOD17A2 GPP (MOD_GPP) and flux tower GPP (EC_GPP) at all 16 flux sites. Site-specific comparison showed a generally good agreement across the sites with R^2 of 0.51 and RMSE of 1.33 g C/(m²·d). However, as shown in Fig. 1, the MODIS GPP product of US-KS2 and IT-Cpz belonging to EBF significantly overestimated the vegetation production but markedly underestimated GPP at the TRF site Br-Sa1. Overall, the MODIS algorithm generally underestimated GPP among the majority of sites belonging to ENF, DBF and MF with relatively small differences. Statistically, the relative mean deviations of ENF, DBF and MF were –26.2%, –15.5% and –11.6%, respectively. All these forest sites represented considerable variations in location, climate, stand age, and species composition; meanwhile, the use of multi-year mean annual GPP can avoid the effect of year-to-year fluctuations. Therefore, it indicated that current MODIS GPP product works well for MF and DBF, moderately for ENF, and poorly for EBF.

3.2 Comparison of seasonal and interannual variations between MODIS GPP and EC-measured GPP

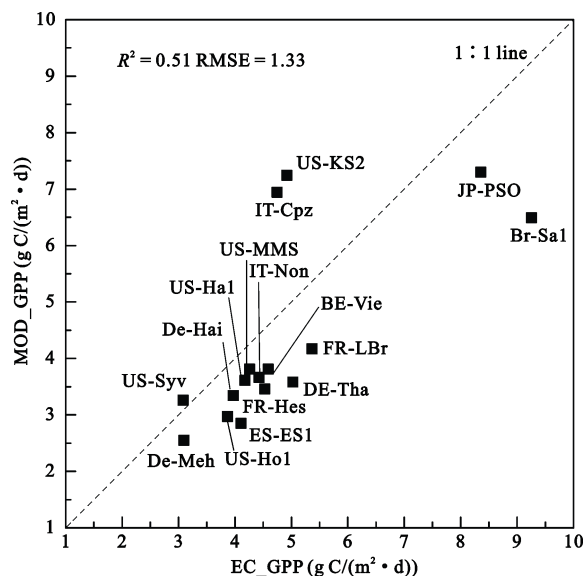Time-series MODIS GPP and EC-measured GPP for the

Fig. 1 Comparisons of multi-year mean annual Moderate Resolution Imaging Spectroradiometer (MODIS) product of MOD17A2 gross primary productivity (GPP) (MOD_GPP) and flux tower GPP (EC_GPP) at all 16 sites. The dash line is the 1∶1 line. R^2 is the coefficient of determination and RMSE is the root-mean-square error (g C/(m²·d)). All the abbreviations in the figure are the site codes listed in Table 1

major forest types including EBF, ENF, DBF and MF were compared at the 8-day and interannual time scales to determine the underlying reasons influencing the performance of multi-year mean annual GPP at the 16 flux sites. Figure 2 illustrates the seasonal traces of GPP derived from tower-based observations and MODIS estimates, and Fig. 3 shows scatter plots of MODIS GPP against tower GPP at 8-day time scale. The largest RMSE was found in EBF (3.05 g C/(m²·d)), followed by DBF (2.45 g C/(m²·d)), ENF (1.87 g C/(m²·d)), and MF (1.52 g C/(m²·d)). Significant bias in GPP estimates for TRF are assumed to explain the RMSE of EBF. Time-series MODIS GPP and EC-measured GPP at BR-Sa1 and JP-PSO also fluctuated severely over nearly the entire year; the result demonstrates that the MODIS algorithm is inapplicable to TRF. However, the MODIS product can adequately capture the broad trends of GPP at both US-KS2 and IT-Cpz flux sites despite the apparent overestimation during the growth season. Slight underestimation was observed in the summertime at all sites of MF and ENF. Nevertheless, the MODIS product showed good performance in capturing the corresponding GPP variations. 8-day MODIS GPP and EC-measured GPP were distributed closely around the 1∶1 line. Seasonal traces and scatter plots at all flux sites of DBF
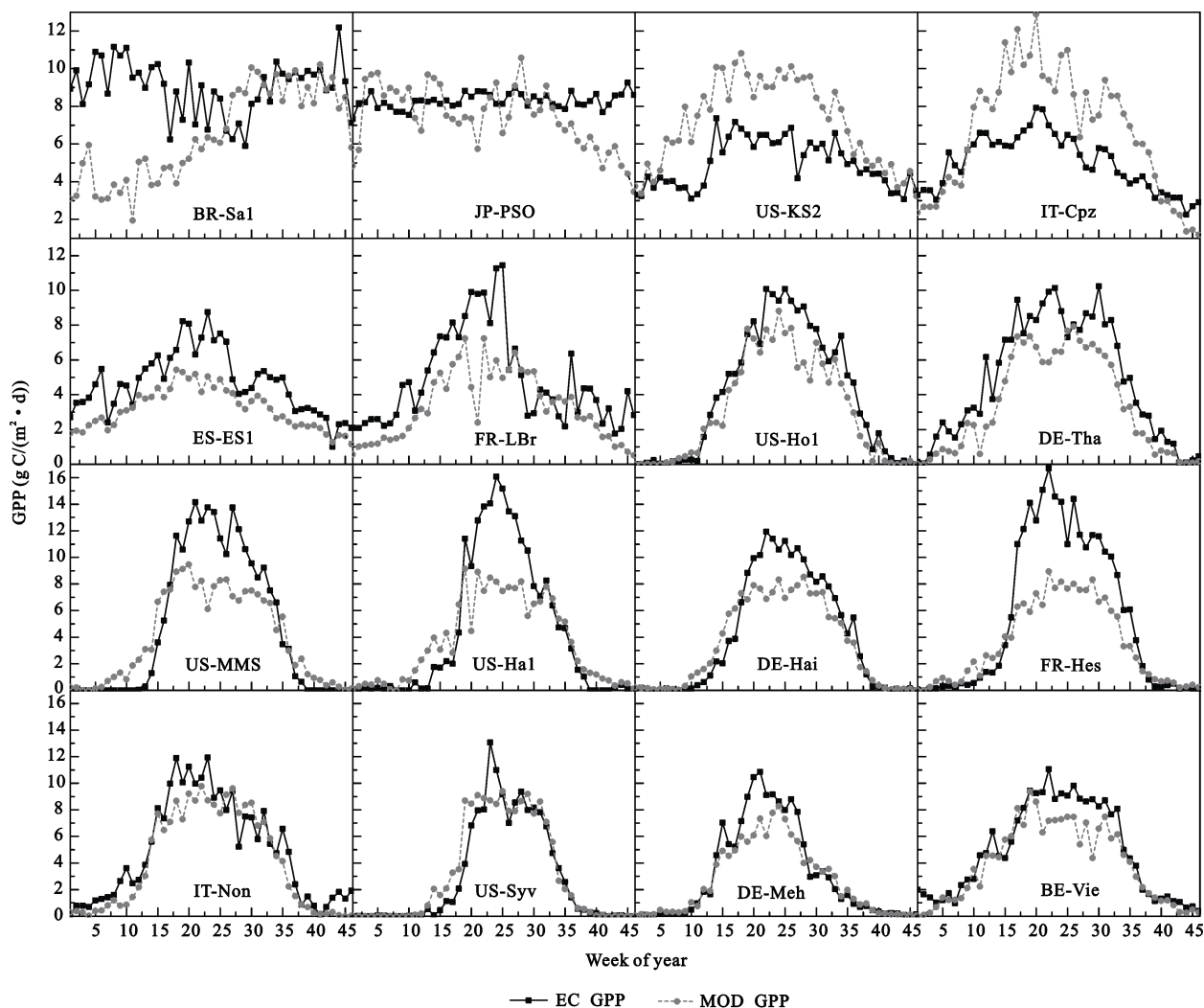
Fig. 2 Seasonal traces of gross primary productivity (GPP) estimated from tower CO_2 flux data (EC_GPP) and MODIS GPP (MOD_GPP) at 8-day time scale for the 16 flux sites including evergreen broadleaf forest (EBF), evergreen needleleaf forest (ENF), deciduous broadleaf forest (DBF), and mixed forest (MF). We only used the first-year data of each flux site in Table 1 to represent the seasonal variations in GPP

showed slight overestimation during the transitions of spring and autumn, but significant underestimations at the peak periods of plants. We further found that the residuals were not randomly distributed. In absolute magnitude, low GPP values were generally in accordance with low prediction errors, whereas high GPP values were greatly underestimated.

Then, we analyzed the agreement between MODIS GPP and EC-measured GPP at the interannual time scale for the main forest types with 68 site-year datasets. For each forest type, 17 years of eddy covariance GPP and MODIS GPP product were obtained. Figure 4 illustrates the scatterplots of mean annual GPP estimates from flux tower sites and the MODIS GPP product for EBF, ENF,

DBF and MF. The best performance was observed in MF (RMSE = 0.68 g C/(m²·d)), followed by ENF (RMSE = 1.31 g C/(m²·d)), DBF (RMSE = 0.95 g C/(m²·d)), and EBF (RMSE = 2.28 g C/(m²·d)). This result can be explained by the transfer of bias from seasonal predictions of GPP. Although RMSE of DBF is lower than that of ENF, the MODIS algorithm severely underestimates the GPP of DBF and is insensitive to large vegetation production.

3.3 Analysis of interannual trends captured by MODIS GPP and EC-measured GPP

Several studies have recently been conducted to monitor and predict terrestrial primary production around the

globe, and explore possible responses to changing climate and environment (Zhao and Running, 2010; Pan *et al*., 2014). However, there remain significant uncertainties associated with the algorithm and data. This study evaluates the interannual trends captured by annual mean GPP estimated from eddy covariance data and by the MOD17A2 GPP product for typical flux sites of each forest type. As shown in Fig. 5, the MODIS GPP of MF at the BE-Vie flux site demonstrated the best performance among the sites surveyed. The tendencies of MODIS GPP and EC-measured GPP were consistent with relatively small differences. Performance of GPP estimates at the DE-Tha site (ENF) was moderate, ac-

companied by an apparent underestimation during these years. The MODIS algorithm showed the weakest performance at the IT-Cpz (EBF) and FR-Hes (DBF) sites. Nonetheless, this algorithm also showed a persistent overestimation of vegetation production at the IT-Cpz site but underestimated flux GPP at the other three forest sites, which can be partly explained by the apparent overestimation during the vegetation seasons for EBF sites including US-KS2 and IT-Cpz in Fig. 2. Furthermore, the algorithm consistently underestimated GPP trends with slight variations and could not capture the drastic tower-based GPP variability at the FR-Hes site.
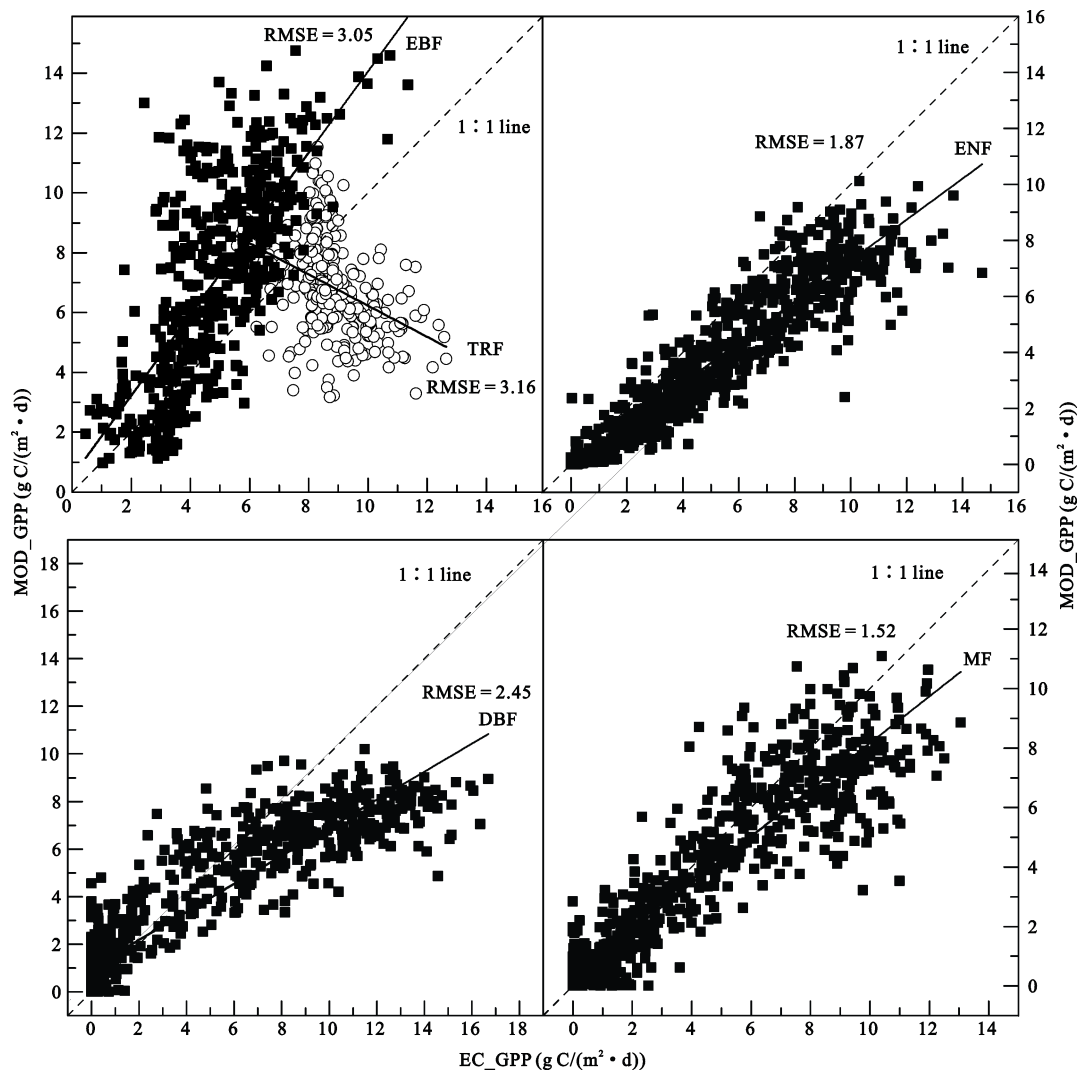

Fig. 3 Comparisons between tower gross primary productivity (GPP) (EC_GPP) and MODIS GPP (MOD_GPP) at 8-day time scale for the major forest types including evergreen broadleaf forest (EBF), evergreen needleleaf forest (ENF), deciduous broadleaf forest (DBF), and mixed forest (MF). In addition, TRF refers to tropical rain forest here. The solid line is the regression line, while the dash line is the 1 ∶ 1 line
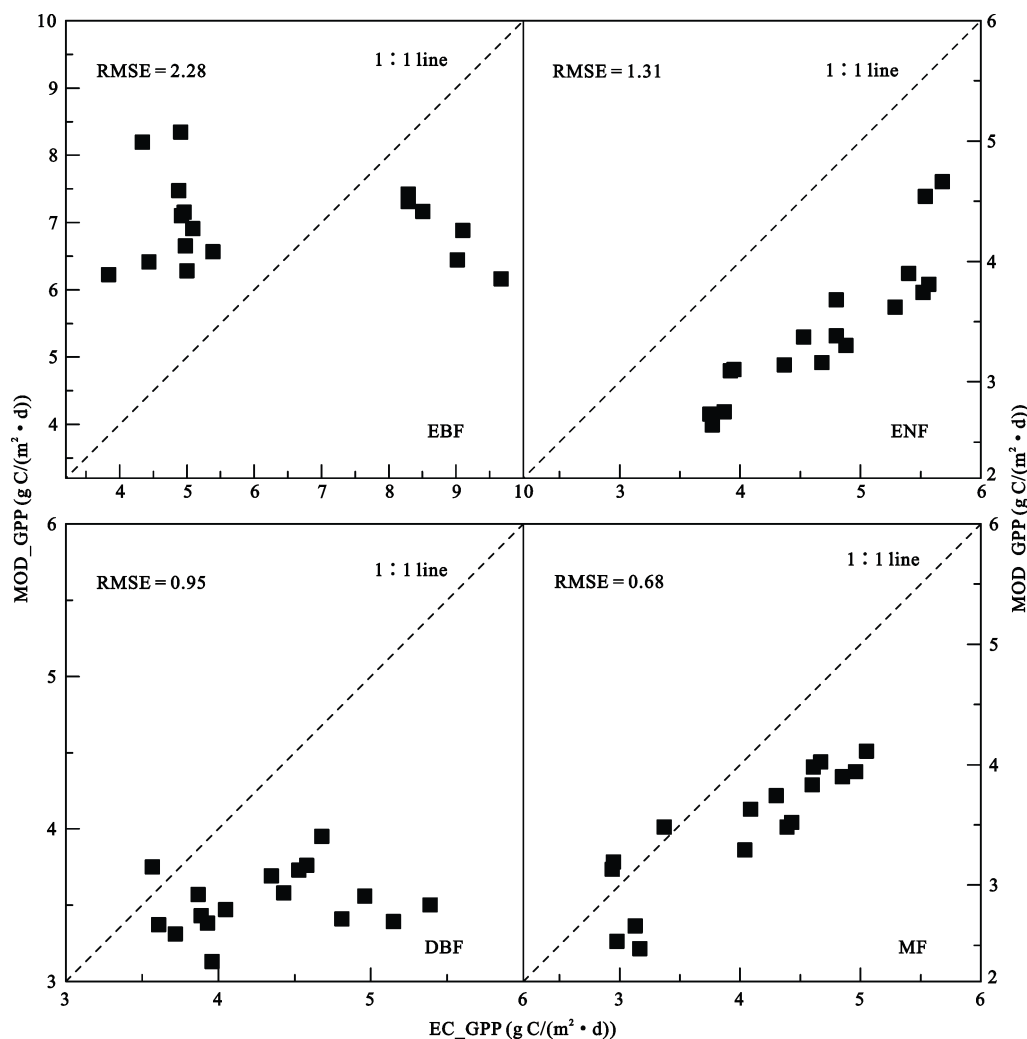
Fig. 4 Comparisons of annual mean gross primary productivity (GPP) estimates from the flux tower sites and the MODIS GPP product for the main forest types including evergreen broadleaf forest (EBF), evergreen needleleaf forest (ENF), deciduous broadleaf forest (DBF), and mixed forest (MF)

4 Discussion and Conclusions

Validation campaign is an important task of satellite-based GPP product because it can evaluate the performance at different temporal and spatial scales. In this study, the degree of correspondence between the EC-measured GPP and the MODIS operational algorithm, which uses broad- scale meteorological data and general biome-specific calibration, was examined. Differences in both MODIS-derived GPP and EC-measured GPP were compared at the seasonal and interannual time scales for the main forest ecosystems, including EBF, ENF, DBF, and MF. Differences in tower and MODIS estimates of GPP may be explained by a number of reasons. Therefore, uncertainties from both MODIS- derived GPP and EC-measured GPP were

analyzed to monitor forest productivity accurately.

4.1 Biophysical variability of photosynthetically active radiation (PAR) conversion efficiency

As a proxy of the conversion efficiency of the incident radiation in PAR, ε varies widely according to the plant functional types (Turner *et al.*, 2003). This variability in ε is also attributed to sub-optimal climatic conditions. To quantify the biome- and climate-induced ranges of ε, MOD17A2 product computed the light use efficiency with a complex ecosystem model (Biome-BGC) and generated a BPLUT that contained parameters for temperature and VPD limits as well as specific leaf area and respiration coefficients for representative vegetation types (Running *et al.*, 2004). However, only minor biome types were defined in this table. Despite the wide
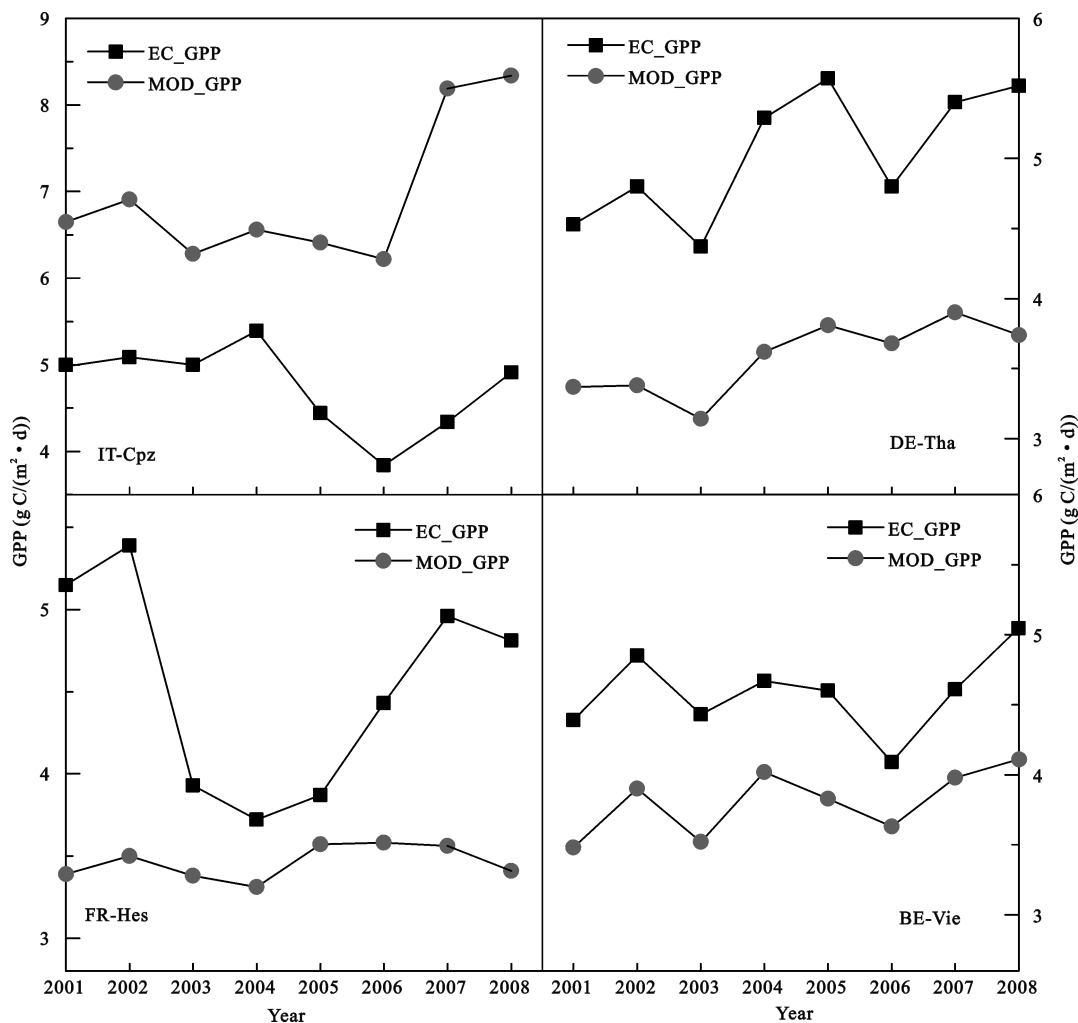
Fig. 5 Assessment of interannual trend of annual mean gross primary productivity (GPP) estimates inferred from eddy covariance data and MOD17A2 GPP product for the typical flux site of per forest type

range of climatic conditions and associated stand structures, soil types, and ages, the same ε was applied indiscriminately, thus introducing large uncertainties into the GPP estimates (Sjöström *et al*., 2013). The MODIS GPP algorithm suggests simple linear ramp functions of climatic variables to calculate the scalars that attenuate the potential ε to produce the final ε used to predict GPP (Turner *et al*., 2003; Heinsch *et al*., 2006). However, a number of studies have concluded that the light use efficiency rate is also dependent on incoming solar radiation and saturates on days with clear sky conditions and high amount of PAR (Turner *et al*., 2003; Lagergren *et al*., 2005). The current BPLUT can not meet requirements for accurate definition of ε, especially for complex and diverse forest ecosystems. Propastin *et al*. (2012) also revealed the disadvantage of using MOD17A2 to estimate the GPP of a moist TRF in In-

donesia and indicated that the ε_{max} value for EBF inapplicable.

4.2 Meteorological data

The NASA Data Assimilation Office (DAO) meteorological data are based on a general circulation model that continuously assimilates observations from space and ground stations with a spatial resolution of 1° by 1.25°. In the C4 MOD17 algorithm, each 1 km pixel falling into the same DAO grid inherits the same meteorological data and creates a noticeable footprint. Such treatment may cause significant inaccuracies at the local scale, specifically in terrains with topographical variations or those located at relatively abrupt climatic gradient zones. To solve this problem, Zhao *et al*. (2006) spatially interpolated the coarse resolution DAO data to the resolution of 1 km pixel using a non-linear interpo-

lation scheme. NCEP/DOE reanalysis 2 data are an improved version of the daily driving meteorological dataset that can fix errors and update parameterizations of physical processes (Kanamitsu *et al.*, 2002). However, analysis of the meteorological data used in the MODIS GPP algorithm continues to show some apparent differences when compared with tower measurements because the initial coarse-spatial resolution data often include biases (Kanniah *et al.*, 2009; Wang *et al.*, 2013). Temperature and VPD are often underestimated, while reanalyzed radiation data generally contain large uncertainties, specifically in areas with high spatial and temporal variability in cloud cover (Liang *et al.*, 2010).

4.3 Uncertainties of MODIS-derived variables

Accurate land cover classification from the MOD12Q1 decision tree algorithm is vital to the success of MODIS GPP calculations (Heinsch *et al.*, 2006). Error propagation must also be considered. The associated fraction of photosynthetically active radiation absorbed by vegetation canopies (FPAR) algorithm uses a structural land cover classification scheme in its calculations (Myneni *et al.*, 1997), while the GPP algorithm depends upon the UMD land cover classification scheme to differentiate among biome types and determine the corresponding light use efficiency for each pixel. Errors in either of these classification schemes can lead to incorrect production estimates (Wu *et al.*, 2010; Sjöström *et al.*, 2013). The current 1 km MODIS global land cover classification unit also poses certain problems because this unit may be too coarse for regional application. Mixed pixels composed of diverse plant functional types may occur, thereby leading to great difficulties in properly describing the variability of biome-specific parameters. For MOD15A2 LAI and FPAR product, the pixel-by-pixel comparison with the ground measurements has a poor correlation and retrieved LAI tends to be overestimated under many conditions (Cohen *et al.*, 2003; Wang *et al.*, 2004). A possible contribution to the overestimation of LAI is the way how it is measured. Flux sites usually measures LAI of the dominant overstory canopy, whereas the MODIS sensor receives reflectance information for a vertically and horizontally integrated canopy. If the dominant canopy is open, as it is at many of these sites, the MOD15 algorithm will consider both overstory and understory surface reflectance as a single canopy unit of the land cover classification, leading to

overestimation of LAI relative to site-based measurements (Heinsch *et al.*, 2006). At the DBF sites, the understory may flush out earlier in the springtime (Fig. 2). In addition, if the forest also contains evergreen needleleaf trees, such as US-Ha1, the algorithm will calculate an LAI and FPAR for a DBF forest canopy prior to actual leaf-out. At EBF sites including US-KS2 and IT-Cpz, both understory and overstory LAI were measured in the field and the MOD15 LAI greatly overestimated the total LAI of these sites, suggesting that sites with open canopies should consider the understory contribution to LAI and GPP estimation.

4.4 Uncertainty of EC-measured GPP

The EC measurements themselves are not free from error. EC-measured GPP values are estimated as the sum of daytime NEP and ecosystem respiration, in which the latter is inferred from the nighttime relationship between EC-measured NEE and the corresponding temperature (Lloyd and Taylor, 1994). Since the EC-method derives daytime respiration using nighttime flux-temperature relationships and ignores reductions in leaf respiration during the day relative to that at night, the method can thus consistently overestimate GPP (Reichstein *et al.*, 2005; Coops *et al.*, 2007) and may be inappropriate for tropical ecosystems (Archibald *et al.*, 2009). Furthermore, uncertainties also arise owing to scale mismatch between the EC footprint and MODIS data. These uncertainties make the direct comparison of field measurements with MODIS data difficult, particularly in the heterogeneous landscapes (Tan *et al.*, 2006; Verma *et al.*, 2014), because retrievals are not ideally centered on the precise location of the pixel used. Particularly in biomes with strong seasonal climates, sub-pixel heterogeneity can produce great biases in remotely-sensed phenology, which affects both observed and modeled GPP in many ecosystems. In principle, greater differences might exist when comparing predicted MOD_GPP with EC_GPP because EC samples only part of the mixed pixel and can not represent other land cover types within the pixel (Chasmer *et al.*, 2009). Referring to other previous studies (Rahman *et al.*, 2005; Xiao *et al.*, 2010; Tang *et al.*, 2012), the average values for the central 3 km × 3 km area from the MODIS product were extracted to better represent the flux tower footprint.

Despite the uncertainties described above, the present

study reveals that satellite-based estimates of MODIS GPP provide relatively accurate observations compared with EC-measured GPP for most forest types. Nevertheless, given the extensive land area occupied by forest ecosystems around the world, the current MODIS-derived GPP product requires further improvements on accuracy for ongoing monitoring of terrestrial ecosystems and provision of continuous measurements of forest productivity.

Acknowledgments

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