A MODIS-based Photosynthetic Capacity Model to estimate gross primary production in Northern China and the Tibetan Plateau

Yanni Gao, Guirui Yu, Huimin Yan, Xianjin Zhu, Shenggong Li, Qiufeng Wang, Junhui Zhang, Yanfen Wang, Yingnian Li, Liang Zhao, Peili Shi

Abstract

Accurate quantification of the spatio-temporal variation of gross primary production (GPP) for terrestrial ecosystems is significant for ecosystem management and the study of the global carbon cycle. In this study, we propose a MODIS-based Photosynthetic Capacity Model (PCM) to estimate GPP in Northern China and the Tibetan Plateau. The PCM follows the logic of the light use efficiency model and is only driven by the Enhanced Vegetation Index (EVI) and the Land Surface Water Index (LSWI). Multi-year eddy CO2 flux data from five vegetation types in North China (temperate mixed forest, temperate steppe) and the Tibetan Plateau (alpine shrubland, alpine marsh and alpine meadow-steppe) were used for model parameterization and validation. In most cases, the seasonal and interannual variation in the simulated GPP agreed well with the observed GPP. Model comparisons showed that the predictive accuracy of the PCM was higher than that of the MODIS GPP products and was comparable with that of the Vegetation Photosynthesis Model (VPM) and the potential PAR-based GPP models. The model parameter (PCmax) of the PCM represents the maximum photosynthetic capacity, which showed a good linear relationship with the mean annual nighttime Land Surface Temperature (LST). With this linear function, the PCM-simulated GPP can explain approximately 93% of the variation in the flux-observed GPP across all five vegetation types. These analyses demonstrated the potential of the PCM as an alternative tool for regional GPP estimation.

1. Introduction

Gross primary production (GPP) is defined as the photosynthetic rate at which plants capture and store chemical energy in a given length of time (Chapin, Matson, & Vitousek, 2011, Chap. 5). GPP is the first step in the input of atmospheric CO2 to terrestrial ecosystems (vegetation and the soil) and a key component of the carbon biogeochemical cycle that links atmospheric CO2 and terrestrial ecosystems (Yuan et al., 2010). Quantifying GPP at regional and global scales is essential for the understanding of the carbon cycle of terrestrial ecosystems and the atmosphere. Its long-term network observations provide valuable information for developing and validating GPP models (Yu et al., 2006; Yuan et al., 2007). Remote sensing (RS) technology repeatedly monitors dynamic changes in terrestrial ecosystem structure and functions at a high temporal–spatial resolution. Its continuous observations play an increasing role in estimating GPP at regional and global scales (Prince & Coward, 1995; Xiao, Hollinger, et al., 2004). Incorporating both EC flux data and RS imagery, many satellite-based GPP models have been developed, e.g., the Vegetation Photosynthesis Model (VPM, Xiao, Hollinger, et al., 2004), the MODIS GPP algorithm (Running et al., 2004), the EC–LUE model (Yuan et al., 2007), the Temperature and Greenness model (TG, Sims et al., 2008), the Vegetation Index model (VI, Wu, Munger, Niu, & Kuang, 2010) and the Greenness and Radiation model (GR, Gitelson et al., 2006, 2012; Peng, Gitelson, Keydan, Rundquist, & Moses, 2011; Peng, Gitelson, & Sakamoto, 2013; Sakamoto, Gitelson, Wardlow, Verma, & Suyker, 2011; Wu, Chen, & Huang, 2011).

Most satellite-based GPP models have been based on the theory of light use efficiency proposed by Monteith (1972, 1977), who suggested that crop productivity is strongly related to the intercepted solar radiation and thus can be estimated as the product of the intercepted solar radiation and its conversion efficiency into plant photosynthate, i.e., light use efficiency (LUE). Based on the method used to estimate...
LUE, these satellite-based GPP models can be classified into two categories. The first category includes those models that employ biome-dependent or biome-independent maximum light use efficiency to calculate LUE, e.g., VPM, the MODIS GPP algorithm and EC–LUE. The general formula for models of this type is as follows:

\[
GPP = \varepsilon_{\text{max}} \times f \times \text{FPAR} \times \text{PAR},
\]

where PAR is the incident photosynthetically active radiation (mol PPFD m\(^{-2}\) s\(^{-1}\) or mol PPFD m\(^{-2}\) d\(^{-1}\)), FPAR is the fraction of PAR absorbed by the plant canopy, the product of FPAR and PAR is the PAR absorbed by the plant canopy (APAR), \(\varepsilon_{\text{max}}\) is the maximum LUE without environmental stresses (mol C mol APAR\(^{-1}\)) and \(f\) is a downward regulating factor for \(\varepsilon_{\text{max}}\) ranging from 0 to 1 under various environmental limiting conditions. Thus, the product of \(\varepsilon_{\text{max}}\) and \(f\) is the actual LUE. Factor \(f\) is usually a function of temperature (\(T\)), soil moisture (SM) and/or water vapor pressure deficit (VPD).

\[
f = f_T \times f_{\text{SM}} \times f_{\text{VPD}}.
\]

Models of this type may differ in their approach to estimate \(\varepsilon_{\text{max}}\) and \(f\) in Eq. (1). For example, the VPM obtains biome-specific \(\varepsilon_{\text{max}}\) from the literature or from the relationship between NEE and incident PAR. The \(f\) of this model includes air temperature (\(T_a\)), land surface water conditions and phenology (Xiao, Hollinger, et al., 2004). The MODIS GPP algorithm uses biome-specific \(\varepsilon_{\text{max}}\) from biome parameter lookup tables, and the low temperature and high VPD are chosen to downregulate \(\varepsilon_{\text{max}}\) (Running et al., 2004). The EC–LUE model sets an invariant \(\varepsilon_{\text{max}}\) across all biomes, and \(f\) equals the minimum value of scalars for the respective effects of \(T\) and soil moisture on \(\varepsilon_{\text{max}}\) according to Liebig’s law (Yuan et al., 2007).

The second category of GPP models, such as TG, VI and GR, involves simplified versions of Eq. (1) based on the relationships between remote sensing data and key factors affecting photosynthesis. Models of this category differ according to the simplified factors. For example, because there are good relationships between Land Surface Temperature (LST) and \(T_a\), VPD and PAR, the TG model is solely driven by LST and the Enhanced Vegetation Index (EVI) from MODIS imagery (Sims et al., 2008). Because the vegetation index is a reliable proxy for both LUE and FPAR, the VI model simply takes the form of GPP \(\propto\) EVI \(\times\) FPAR \(\times\) PAR (Wu, Munger, et al., 2010). It has been reported that both GPP and the vegetation index have close relationships with canopy chlorophyll content. Thus, the GR model estimates GPP based on the product of the vegetation index and either incident PAR or potential PAR (Gitelson et al., 2006, 2012; Peng et al., 2011, 2013; Sakamoto et al., 2011; Wu et al., 2011).

The first category of GPP models requires ground meteorological observations as input variables. These observations usually have insufficiently detailed temporal and spatial resolution and introduce simulation errors into the outputs for large areas (Rahman, Sims, Cordova, & El-Masri, 2005; Sims et al., 2006, 2008). The GPP models in the second category reduce or avoid their dependence on ground meteorological observations. These features promote their application at regional and global scales. However, the ecological meaning of the model parameters is not nearly as clear as that of the parameters in the first category of GPP models (Yang, Shang, Guan, & Jiang, 2013). Accordingly, the principal goal of this paper is to develop an entirely satellite-based GPP model in which the model parameter has a clear ecological meaning. The specific objectives are as follows: (1) to apply the flux data from five vegetation types in North China and the Tibetan Plateau to parameterize and validate the model, (2) to explore the possibility of using remote sensing data to simulate the spatial variation in the model parameter, (3) to analyze the seasonal and inter-seasonal dynamics of the simulated GPP and (4) to compare the predictive accuracy of the PCM with that of the MODIS GPP products and the VPM.

### 2. Model description

#### 2.1. Model structure

According to Monteith’s (1972, 1977) logic, incident PAR (\(\text{PAR}\)) is the energy source for photosynthesis and is included as an important variable in LUE models. Over short time periods (minutes to hours), photosynthesis increases with the increase in \(\text{PAR}\) under light-limited conditions. When \(\text{PAR}\) exceeds what plants need, photosynthesis begins to saturate and then tends to decrease (e.g., Alton, North, & Los, 2007; Ibmrom et al., 2008; Lagergren et al., 2005; Propastin, Ibmrom, Knohl, & Erasmi, 2012; Sims et al., 2005; Turner et al., 2003; Zhang et al., 2011). In contrast to the results on an hourly time scale, daily \(\text{PAR}\) has a very weak relationship with daily gross photosynthesis within many types of ecosystems, even during the peak growing season, when \(\text{PAR}\) has the strongest direct effect on photosynthesis (Sims et al., 2005). The daily \(\text{PAR}\) in the Arctic is nearly the same as that in the tropics during midsummer; however, the tropics have a greater daily carbon gain than the Arctic (Chapin et al., 2011, Chap. 5). The annual \(\text{PAR}\) also has no relationship with annual GPP across biomes from tundra to rainforest (Gurbalski et al., 2010).

It was reported that \(\text{PAR}\) can introduce unpredictable uncertainty in GPP estimation for crops due to variable atmospheric conditions such as clouds, aerosols and water vapor (Gitelson et al., 2012; Peng et al., 2013). Potential \(\text{PAR}\) (\(\text{pPAR}\)) can be considered as the maximal value of \(\text{PAR}\) that may occur when the concentrations of atmospheric aerosols and gases are minimal, which excludes the frequent fluctuations in \(\text{PAR}\) and has been shown to perform more satisfactorily than \(\text{PAR}\) in GPP estimation for crops (Gitelson et al., 2012; Peng et al., 2013). The likely reason for this outcome is that the acclimation and adaptation mechanisms of plants to unfavorable light conditions can maximize light absorption and minimize light damage by adjusting their physiological and genetic features (e.g., Chapin et al., 2011, Chap. 5; Ehleringer, Björkman, & Mooney, 1976; Koller, 2000; Taiz & Zeiger, 2002, Chap. 9). The \(\text{pPAR}\) during the growing season can be expressed as the product of the maximum \(\text{pPAR}\) (\(\text{pPAR}_{\text{max}}\), mol PPFD m\(^{-2}\) d\(^{-1}\)) and a down-regulated factor that varies with the day of a year (\(\text{pPAR}_{\text{d}}\)). If we use \(\text{pPAR}\) in place of \(\text{PAR}\) in Eq. (1), we obtain the following result:

\[
\text{GPP} = (\varepsilon_{\text{max}} \times \text{pPAR}_{\text{max}}) \times (\text{FFPAR} \times \text{pPAR}_{\text{d}}) \times f.
\]

The product of \(\varepsilon_{\text{max}}\) and \(\text{pPAR}_{\text{max}}\) represents the maximum photosynthetic capacity (termed \(\text{PC}_{\text{max}}\), mol C m\(^{-2}\) d\(^{-1}\)), and the product of FPAR and \(\text{pPAR}_{\text{d}}\) is a down-regulated factor that varies with the absorbed \(\text{PAR}\), which can be used to represent the variability of photosynthetic capacity under different growth stages (\(\text{PC}_{\text{d}}\)). Photosynthetic capacity is defined as the photosynthetic rate under favorable environmental conditions (Chapin et al., 2011, Chap. 5). Thus, the LUE model can be converted into the following model based on the concept of photosynthetic capacity:

\[
\text{GPP} = \text{PC}_{\text{max}} \times \text{PC}_{\text{d}} \times f.
\]

This equation specifies the general form of our developed GPP model, termed the Photosynthetic Capacity Model (PCM). Photosynthetic capacity depends on the amount of photosynthetic apparatus within a plant community and can be directly expressed by the total content of canopy chlorophyll (Gitelson, Viña, Giganda, & Arkebauer, 2005; Medina & Lieth, 1964; Muraoa & Koizumi, 2005; Peng et al., 2011; Schlemmer et al., 2013; Whitaker & Marks, 1975). A number of studies have explored methods of estimating canopy chlorophyll content from vegetation indices. Such estimation has been shown to be feasible and can provide acceptable accuracy (Gitelson et al., 2005; Hunt et al., 2013). EVI has been reported to show close correlations with chlorophyll content at both the leaf and the canopy levels (Huang et al., 2005; Ibrom, Knohl, & Erasmi, 2012; Sims et al., 2005; Turner et al., 2003; Zhang et al., 2011). In contrast to the results on an hourly time scale, daily \(\text{PAR}\) has a very weak relationship with daily gross photosynthesis within many types of ecosystems, even during the peak growing season, when \(\text{PAR}\) has the strongest direct effect on photosynthesis (Sims et al., 2005). The daily \(\text{PAR}\) in the Arctic is nearly the same as that in the tropics during midsummer; however, the tropics have a greater daily carbon gain than the Arctic (Chapin et al., 2011, Chap. 5). The annual \(\text{PAR}\) also has no relationship with annual GPP across biomes from tundra to rainforest (Gurbalski et al., 2010).
110


...112; Ide, Nakaji, & Oguma, 2010; Muraoka et al., 2013; Nagai, Saigusa, Muraoka, & Nasahara, 2010; Wu, Munger, et al., 2010). Biophysical research has also indicated that EVI is sensitive to canopy variations and is barely saturated in multi-layered and closed canopies (Huete et al., 2002; Xiao, Hollinger, et al., 2004). Because EVI is readily obtained at high temporal and spatial resolution from satellite imagery, it is used to represent the variability of photosynthetic capacity in this version of the PCM.

Under actual environmental conditions, photosynthesis is limited by environmental stress. It has been reported that moisture is a key factor controlling plant photosynthesis, e.g., in semidesert grassland in southeastern Arizona, USA (Scott, Hamerlynck, Jenerette, Moran, & Barron-Gafford, 2010) and in savanna in Africa (Sjöström et al., 2011). Research at 28 AmeriFlux and EuroFlux sites, including five major terrestrial biomes (deciduous broadleaf forest, mixed forest, evergreen needleleaf forest, grassland and savanna), has indicated that moisture conditions control photosynthesis at most sites except at the beginning and end of the growing season when temperature controls photosynthesis in certain ecosystems (Yuan et al., 2007). Phenological studies have indicated that the accumulated temperature above a certain threshold agrees well with the timing of bud break in boreal ecosystems (Linkosalo, 2000); in temperate Eastern China, the spatial patterns of the mean spring and autumn air temperatures were significantly correlated with those of the beginning and ending dates of the growing season, respectively (Chen, Hu, & Yu, 2005). This relationship between temperature and photosynthesis at the beginning and end of the growing season can also be represented appropriately by an EVI time series (Zhang et al., 2003).

Soil moisture is the source of water for plant growth, and VPD indicates the evaporative demand in the atmosphere. Plant photosynthesis depends primarily on the dynamics of both soil moisture and VPD (Xiao, Hollinger, et al., 2004). A number of light use efficiency models use soil moisture and/or VPD to mirror the effect of moisture conditions on photosynthesis (Potter et al., 1993; Prince & Goward, 1995; Running et al., 2004). However, it is difficult to quantify soil moisture across large areas based on either remote sensing or modeling, and this difficulty limits the spatial application of soil-moisture dependent models (Yuan et al., 2007). The VPM developed a moisture index ($W_{\text{scalar}}$) as an alternative to represent the dynamic change of canopy water content (Xiao, Hollinger, et al., 2004). $W_{\text{scalar}}$ has been successfully applied in GPP estimation in many ecosystems, e.g., evergreen needleleaf forest (Xiao, Hollinger, et al., 2004), deciduous broadleaf forest (Xiao, Zhang, et al., 2004), tropical evergreen forest (Xiao et al., 2005), cropland (Kalfas, Xiao, Vaneugas, Verma, & Suyker, 2011; Yan et al., 2009), grassland (Wu et al., 2008), shrubland (Li et al., 2007) and wetland (Li et al., 2007). Because $W_{\text{scalar}}$ can also be calculated from easily obtained remote sensing data, it is used to represent the seasonal variation of canopy water content in this version of the PCM.

2.2. Model algorithms

From the above specifications, the PCM can be expressed as follows:

$$\text{GPP} = P_{\text{max}} \times \text{EVI}_s \times W_s.$$  \hfill (5)

where $P_{\text{max}}$ stands for the maximum photosynthetic capacity for a certain region (e.g., mol C m$^{-2}$ d$^{-1}$). EVI$_s$ represents the variability of photosynthetic capacity and $W_s$ indicates the moisture conditions that downward regulate photosynthetic capacity. The values of EVI$_s$ and $W_s$ are set to zero before and after the growing season, when photosynthesis does not occur. The beginning and end of the growing season are identified from the EVI time series (Zhang et al., 2003).

Because GPP is almost 0 when EVI is approximately 0.1 (Sims et al., 2006), the equation developed for the TG model is used as follows to represent the variability of photosynthetic capacity (Sims et al., 2008):

$$\text{EVI}_s = \text{EVI} - 0.1.$$  \hfill (6)

### Table 1

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>Site name</th>
<th>Code</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Mean annual temperature (°C)</th>
<th>Mean annual precipitation (mm)</th>
<th>Data available period</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad-leaved Korean pine mixed forest</td>
<td>Changbaishan</td>
<td>CBS</td>
<td>42.40</td>
<td>128.10</td>
<td>0.9 – 4.0</td>
<td>600 – 810</td>
<td>2003 – 2008</td>
<td>Zhang et al. (2009)</td>
</tr>
<tr>
<td>Temperate steppe</td>
<td>Inner Mongolia</td>
<td>NM</td>
<td>43.55</td>
<td>116.68</td>
<td>– 0.4</td>
<td>350.9</td>
<td>2004 – 2008</td>
<td>Wu et al. (2008)</td>
</tr>
<tr>
<td>Alpine marsh</td>
<td>Haibe</td>
<td>HBSD</td>
<td>37.61</td>
<td>101.31</td>
<td>– 1.7</td>
<td>600</td>
<td>2004 – 2008</td>
<td>Li et al. (2007)</td>
</tr>
<tr>
<td>Alpine meadow-steppe</td>
<td>Damxung</td>
<td>DX</td>
<td>30.85</td>
<td>91.08</td>
<td>1.3</td>
<td>480</td>
<td>2004 – 2009</td>
<td>Fu et al. (2009)</td>
</tr>
</tbody>
</table>

### Fig. 1

The relationship between the observed GPP and EVI$_s \times W_s$ based on an 8-day average. $W_s$: moisture index. A: temperate mixed forest (CBS), B: temperate steppe (NM), C: alpine shrubland (HBGC), D: alpine marsh (HBSD), and E: alpine meadow-steppe (DX).
The EVI is computed from the following equation (Huete et al., 2002):

\[
EVI = G \times \frac{\rho_{\text{nir}} - \rho_{\text{red}}}{\rho_{\text{nir}} + (C_1 \times \rho_{\text{red}} - C_2 \times \rho_{\text{blue}}) + L},
\]

where \( G = 2.5 \), \( C_1 = 6.0 \), \( C_2 = 7.5 \), \( L = 1 \) and \( \rho_{\text{nir}}, \rho_{\text{red}} \) and \( \rho_{\text{blue}} \) are the spectral reflectances of the near infrared, red, and blue bands in MODIS imagery, respectively (Huete et al., 2002).

The \( W_i \) is modified as follows from the equation for \( W_{\text{scalar}} \) (Xiao, Hollinger, et al., 2004):

\[
W_{\text{scalar}} = \frac{1 + LSWI}{1 + LSWI_{\text{max}}},
\]

where LSWI is the Land Surface Water Index and LSWI_{max} is the maximum LSWI during the growing season for each pixel (Xiao, Hollinger, et al., 2004). Because the values of \( W_{\text{scalar}} \) depend upon LSWI_{max}, there may be similar or identical \( W_{\text{scalar}} \) values under different vegetation types even though their actual canopy water content varies considerably. Thus, \( W_{\text{scalar}} \) can represent a temporal dynamic but spatial pattern of moisture conditions. In this version of the PCM, LSWI_{max} was assumed to be 1 to allow spatial comparison. The modified equation for \( W_{\text{scalar}} \), i.e., \( W_s \), is capable of representing both temporal and spatial variation in moisture conditions.

The equation for LSWI is as follows (Xiao, Hollinger, et al., 2004):

\[
LSWI = \frac{\rho_{\text{nir}} - \rho_{\text{swir}}}{\rho_{\text{nir}} + \rho_{\text{swir}}},
\]

where \( \rho_{\text{nir}} \) and \( \rho_{\text{swir}} \) are the spectral reflectances of the near infrared and short infrared bands in MODIS imagery, respectively (Xiao, Hollinger, et al., 2004).

3. Data and methods

3.1. Description of study sites

The multi-year flux and meteorology data used in this study were collected from five natural vegetation types with eddy-covariance towers operating in the Chinese Terrestrial Ecosystem Flux Observational Network (ChinaFLUX), including temperate mixed forest (the broad-leaved Korean pine mixed forest in the Changbai Mountains, CBS) and temperate steppe (NM) in North China and alpine shrubland (HBGC), alpine marsh (HBSD) and alpine meadow-steppe (DX) on the Tibetan Plateau. The mean annual precipitation (MAP) is 600–810 mm in CBS, approximately 600 mm in HBGC and HBSD, and 480 mm in DX. The water supply is almost not limited in these vegetation types. NM is located in the semi-arid region with an MAP of 350.9 mm, and water is a dominant factor. A brief description of these vegetation types is presented in Table 1. Detailed information about the climate, vegetation and soil in each vegetation type can be found in the references in Table 1.

3.2. Flux data

Subtracting net ecosystem exchange of CO₂ (NEE; a negative sign denotes carbon entering the ecosystem from the atmosphere, whereas a positive sign denotes carbon release from the ecosystem into the atmosphere) from ecosystem respiration (\( R_e \)) gives gross primary production (GPP). NEE was directly measured by the eddy covariance approach. A method presented by Reichstein et al. (2005) was used to estimate \( R_e \). The detailed procedures are presented below.

The original observed half-hourly NEE values were processed by three-dimensional coordinate rotation, WPL correction, storage correction (only for the forest site), and filtering to exclude invalid data (Yu et al., 2006). Missing daytime NEE values (when the solar elevation angle \( \geq 0 \)) were calculated with the Michaelis–Menten equation (Michaelis & Menten, 1913). Daytime \( R_e \) values were calculated with the Lloyd and Taylor model using the soil temperature at 5 cm depth as the input variable (Lloyd & Taylor, 1994; Reichstein et al., 2005). Valid nighttime NEE (i.e., nighttime respiration when the solar elevation angle \( < 0 \)) and the soil temperature at 5 cm depth were used to estimate the activation energy parameter (\( E_0 \)) of the Lloyd and Taylor model every 5 days using a 15-day moving window. The final \( E_0 \) for the whole year was calculated as the average of the three \( E_0 \) with the smallest standard errors. The reference respiration (\( R_{r0} \)) for the Lloyd and Taylor model was estimated every 5 days using a 10-day moving window.

Based on the filled half-hourly daytime NEE data and the calculated daytime \( R_e \), half-hourly GPP values were obtained and then summed to yield daily values. The site-years with more than 10% of the daily GPP values missing were NM in 2006, HBSD in 2007 and DX in 2008. To be consistent with the time scale of the MODIS images, the flux and meteorology data were separately averaged within the same 8-day periods.

3.3. Remote sensing data

EVI, LSWI and MOD11A2 LST products were downloaded from the University of Oklahoma Data Center (http://www.eomf.ou.edu/visualization/manual/). The MOD17 GPP products were downloaded from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC. 2012. MODIS subsetted land products, Collection 5. Available on-line [http://daac.ornl.gov/MODIS/modis.html] from ORNL DAAC, Oak Ridge, Tennessee, U.S.A. Accessed 3 29, 2013). All MODIS images were 8-day composites. EVI and LSWI have a spatial resolution of 500 m, and the MOD11A2 LST and the MOD17 GPP products have a temporal resolution of 8 days.

Table 2

<table>
<thead>
<tr>
<th>Site code</th>
<th>Parameterization</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( PC_{\text{max}} ) (mol C m(^{-2}) d(^{-1}))</td>
<td>( r^2 )</td>
</tr>
<tr>
<td>CBS</td>
<td>2.61</td>
<td>0.92</td>
</tr>
<tr>
<td>NM</td>
<td>2.06</td>
<td>0.81</td>
</tr>
<tr>
<td>NM(^a)</td>
<td>2.18</td>
<td>0.83</td>
</tr>
<tr>
<td>HBGC</td>
<td>1.75</td>
<td>0.95</td>
</tr>
<tr>
<td>HBSD</td>
<td>1.38</td>
<td>0.90</td>
</tr>
<tr>
<td>DX</td>
<td>2.00</td>
<td>0.83</td>
</tr>
</tbody>
</table>

\(^a\) The site-year 2005 was excluded from model parameterization and validation due to severe drought. This \( PC_{\text{max}} \) was chosen as the maximum photosynthetic capacity in NM.
spatial resolution of 1 km. The pixels in which the flux towers were located were chosen in this study.

3.4. Parameterization and validation

Multi-year eddy CO2 flux data from five vegetation types in North China (temperate mixed forest and temperate steppe) and the Tibetan Plateau (alpine shrubland, alpine marsh, and alpine meadow-steppe) were used for model parameterization and validation. The site-years with more than 10% of the observed daily GPP values missing, i.e., NM in 2006, HBSD in 2007 and DX in 2008, were excluded from both analyses.

All effective site-year data were used to estimate the model parameter ($P_{\text{Cmax}}$) for each vegetation type. $P_{\text{Cmax}}$ was taken as the slope of the relationship between the observed GPP and the product of EVIs and $W_s$. The model was validated using the method of training/validation splitting cross-validation (Migliavacca et al., 2011). The data for each site-year were excluded one at a time, with the remaining site-years as the training data to fit the model parameter, and then to predict the excluded site-year. During the model validation, statistics were calculated and averaged for each vegetation type to assess the performance of the model. The statistics include the coefficient of determination ($r^2$), standard error ($SE$), mean normalized bias (MNB), root mean square error (RMSE) and modeling efficiency ($EF$).

$$r^2 = \frac{\sum_{i=1}^{n} \left( x_i - \bar{x} \right) \left( y_i - \bar{y} \right)^2}{\sqrt{\sum_{i=1}^{n} \left( x_i - \bar{x} \right)^2 \cdot \sum_{i=1}^{n} \left( y_i - \bar{y} \right)^2}}$$

$$SE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n}}$$

Fig. 2. The relationship between maximum photosynthetic capacity ($P_{\text{Cmax}}$) and mean annual nighttime LST (LST$_{an}$). CBS: temperate mixed forest, NM: temperate steppe, HBGC: alpine shrubland, HBSD: alpine marsh, and DX: alpine meadow-steppe.

Fig. 3. The seasonal and interannual variation in the observed GPP and simulated GPP, based on an 8-day average. The open dots denote the observed GPP, and the black lines denote the simulated GPP. A: temperate mixed forest (CBS), B: temperate steppe (NM), C: alpine shrubland (HBGC), D: alpine marsh (HBSD), and E: alpine meadow-steppe (DX).
MNB = \frac{1}{n} \sum_{i=1}^{n} \left( y_i - \bar{x} \right), \quad (12)

\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - y_i)^2}{n}}, \quad (13)

EF = 1 - \frac{\sum_{i=1}^{n} (x_i - y_i)^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2}, \quad (14)

where the \( x_i \) are the observed data, the \( y_i \) are the simulated data and \( \bar{x} \) and \( \bar{y} \) are the averages of the observed and simulated data, respectively. The quantity \( r^2 \) represents the fraction of the variation in the observed data that can be explained by the model. MNB and RMSE are used to measure the biases that cause the simulated data to differ from the observations. EF represents the consistency of the observed values with the simulated values and is sensitive to the systematic deviation. EF can range from \(-\infty\) to 1. An efficiency of 1 (\( EF = 1 \)) corresponds to a perfect match between the simulated data and the observed data. An efficiency of 0 (\( EF = 0 \)) indicates that the model estimates are as accurate as the mean of the observed data. An efficiency less than 0 (\( EF < 0 \)) indicates that the observed mean is a better predictor than the model.

4. Results

4.1. \( PC_{\text{max}} \)

The observed 8-day average GPP was linearly related to EVI \( \times W_s \) in each vegetation type (Fig. 1), and the slope of this linear relationship was identified as the maximum photosynthetic capacity (\( PC_{\text{max}} \), mol C m\(^{-2}\) d\(^{-1}\)). The model parameterization showed that \( PC_{\text{max}} \) was lowest in HBSD, highest in CBS and similar in NM and DX (Table 2). Due to a severe drought in NM in 2005 (precipitation was less than 200 mm), this site-year was removed from the model parameterization.

A regression analysis of \( PC_{\text{max}} \) as a function of the ground-observed mean annual daily air temperature (MAT), nighttime air temperature (MAT\(_n\), when the solar elevation angle \( \leq 0 \)), daytime air temperature (MAT\(_d\), when the solar elevation angle \( \geq 0 \)) or precipitation (MAP) during the study periods indicated that \( PC_{\text{max}} \) had significant relationships with MAT and MAT\(_n\) (Table 3). Because of the strong relationship between the MAT\(_n\) and the mean annual nighttime Land Surface Temperature (LST\(_{an}\)) from MODIS LST products, LST\(_{an}\) can explain...
approximately 86% of the variation in PC\textsubscript{max} (Table 2). Thus, the following linear equation in \textit{LST}_\text{an} can be used to estimate the spatial variation in PC\textsubscript{max} (Fig. 2):

\[
\text{PC}_{\text{max}} = 0.1346 \times \text{LST}_\text{an} + 2.7522. \tag{15}
\]

4.2. Seasonal and inter-seasonal dynamics of the PCM-estimated GPP

Using the parameterized PC\textsubscript{max} in Table 2, the PCM was executed to estimate GPP for all site-years for each vegetation type (Fig. 3). In most cases, the beginning and ending dates of the simulated GPP agreed well with those of the observed GPP, and the simulated maximal GPP was also in good agreement with the observed maximal GPP. The PCM-simulated GPP and the flux-observed GPP displayed most consistent seasonal and inter-seasonal variations in HBGC, followed by CBS and HBSD (Table 2, Fig. 3A, C and D). However, NM and DX showed several obvious gaps. When a severe drought occurred, i.e., during 2005 in NM (Fig. 4B), a large discrepancy resulted between the simulated GPP and the observed GPP (Fig. 3B). When the vegetation was very sparse, e.g., at the early stage of the 2009 growing season in DX (Fig. 4E), the beginning date of the simulated GPP obviously lagged behind that of the observed GPP (Fig. 3E). These results indicated that the PCM performs well in GPP estimation except under conditions of serious drought and very sparse vegetation.

4.3. Comparison of the predictive accuracy of the PCM with the MODIS GPP products and the VPM

Across the studied vegetation types, the statistics from the model validation were similar to the values from the model parameterization (Table 2). The model validation showed that the PCM can predict 84–95% of the variation in the observed GPP.

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Fig. 5. Comparisons of the observed GPP with the predicted GPP from the PCM, the MODIS GPP products and the VPM, based on an 8-day average. The plots are derived from the last year of the time series for each vegetation type (Table 1). \( r^2 \): coefficient of determination, SE: standard error of the simulated GPP (mol C m\(^{-2}\) d\(^{-1}\)), MNB: mean normalized bias, RMSE: root mean square error (mol C m\(^{-2}\) d\(^{-1}\)), and EF: modeling efficiency. In the VPM, the phenology factor was set to 1, and the minimum, maximum and optimum temperatures for photosynthetic activities were separately assumed to be 0, 35 and 20 °C, for all five vegetation types (for details see Wu et al. (2009) for CBS, Li et al. (2007) for HBGC and HBSD, and Li et al. (2007) and Liu, Chen, and Han (2012) for NM and DX). PAR was calculated from shortwave radiation (SW) using the equation of \( SW \approx 0.505 \times \text{PAR} \) (Unit: PAR, mol m\(^{-2}\) s\(^{-1}\); SW, W m\(^{-2}\); Mahadevan et al., 2008).

Fig. 6. The observed GPP plotted against (I) half-hourly incident PAR (inPAR) during the peak growing season of the first year in Table 1 (taken as an example), (II) daily inPAR during the growing season for the study periods and (III) 8-day average inPAR during the growing season for the study periods. The inPAR was calculated from shortwave radiation (SW) using the equation of \( SW \approx 0.505 \times \text{PAR} \) (Unit: PAR, mol m\(^{-2}\) s\(^{-1}\); SW, W m\(^{-2}\); Mahadevan et al., 2008). A: temperate mixed forest (CBS), B: temperate steppe (NM), C: alpine shrubland (HBGC), D: alpine marsh (HBSD), and E: alpine meadow-steppe (DX).
To further assess the performance of the PCM in GPP prediction, one-year data (the last year of the time series for each vegetation type) in Table 1 were chosen to compare the predictive accuracy of the PCM with that of the MODIS GPP products and the VPM. The MODIS GPP products are the principal source of GPP at regional and global scales (Running et al., 2004; http://daac.ornl.gov/MODIS/modis.html), and the VPM is a MODIS-based LUE model and has been validated in four of our studied vegetation types (Li et al., 2007; Wu et al., 2008, 2009; Zhang et al., 2009). Plots of the predicted GPP against the observed GPP for these three models are presented in Fig. 5. According to the values of the statistics, the predictive accuracy of the PCM was higher than that of the MODIS GPP products and comparable with the VPM. The regression line of the observed GPP vs. either the PCM-predicted GPP or VPM-predicted GPP was very close to the 1:1 line. The MODIS GPP products appeared to overestimate the lower values of the observed GPP and to underestimate the higher values of the observed GPP. Similar biases of the MODIS GPP products have also been reported in other studies (e.g., He et al., 2013; Turner et al., 2006; Zhang, Yu, Jiang, & Tang, 2008).

5. Discussion

5.1. Impact of photosynthetically active radiation on photosynthesis

As the essential energy source, incident PAR (inPAR) is an important input variable in light use efficiency models (e.g., Monteith, 1972; Potter et al., 1993; Prince & Goward, 1995; Xiao, Hollinger, et al., 2004). In our study region during the peak growing season, when inPAR has the most direct influence on photosynthesis (Fig. 6I), there are generally three types of relationships between GPP and inPAR over short time periods (minutes to hours): positive (light limited), irrelevant (light saturation) and negative (light exceeds what plants need). If the half-hourly GPP and inPAR were summed to obtain daily values (Fig. 6II) or further averaged to 8-day values over the growing season in the study periods (Fig. 6III), GPP had little or no relationship with inPAR. Although the GPP-inPAR response was analyzed separately for each site-year, $r^2$ was nearly as low as in the all site-years in each vegetation type (data not shown). These results indicated that inPAR only slightly constrains photosynthesis on an 8-day time scale in our studied vegetation types.

Fig. 7. Comparison between the observed GPP and the predicted GPP, based on an 8-day average. The predicted GPP values were calculated from five formulas for the GPP model, with the following driving variables: A, EVIs alone; B, EVIs $\times$ incident PAR (EVIs $\times$ inPAR); C, EVIs $\times$ potential PAR (EVIs $\times$ pPAR); D, EVIs $\times$ potential PAR $\times$ Ws (EVIs $\times$ pPAR $\times$ Ws); and E, EVIs $\times$ Ws (i.e., the PCM). The data are derived from the last year of the time series for each vegetation type (Table 1). Ws: moisture index. The open dots denote the observed GPP, and the black lines denote the predicted GPP.
The temporal variability of inPAR during growing season reflects two types of variation: low-frequency variation due to seasonal change in the hours of sunshine (i.e., day length) and high-frequency variation caused by constantly changing atmospheric conditions (Gitelson et al., 2012; Sakamoto et al., 2011). It has been showed that the high-frequency variation in inPAR can introduce large uncertainties into crop GPP estimation, whereas potential PAR (pPAR), which represents only the low-frequency variation in inPAR, performs better than inPAR (Gitelson et al., 2012; Peng et al., 2013). Unlike the PCM, which uses EVI to represent the photosynthetic capacity, many studies have employed EVI to indicate the fraction of PAR absorbed by the photosynthetically active parts of the plant canopy (Kalfas et al., 2011; Li et al., 2007; Wu et al., 2008; Xiao, Hollinger, et al., 2004; Xiao, Zhang, et al., 2004; Xiao et al., 2005; Yan et al., 2009). To identify the weight of each item in GPP estimation, $\nu$, $\sigma$, and $\tau$, the spatial application of TEMP-based GPP models. Furthermore, temperature primarily controls photosynthesis at the beginning and end of the growing season (Chen et al., 2005; Linkosalo, 2000; Yuan et al., 2007), which can be represented effectively by the EVI time series (Zhang et al., 2003). Thus, the PCM does not include temperature as a constraint. However, whether the PCM is effective in GPP estimation when the temperature is extremely high or low has not been examined because these conditions did not occur during the study period (Fig. 4).

Table 4
The statistics of the predicted GPP from five formulas for the GPP model, which were separately driven by EVI alone, EVI × incident PAR (EVI × inPAR), EVI × potential PAR (EVI × pPAR), EVI × potential PAR × Wc (EVI × pPAR × Wc) and EVI × Wc (i.e. the PCM). The data are derived from the last year of the time series for each vegetation type (Table 1). Wc: moisture index, $r^2$: coefficient of determination, SE: standard error of the simulated GPP, MNB: mean normalized bias, RMSE: root mean square error, and EF: modeling efficiency. CBS: temperate mixed forest; NM: temperate steppe; HBGC: alpine shrubland; HBSD: alpine marsh, and DX: alpine meadow-steppe.

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<th>Site code</th>
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<th>$r^2$</th>
<th>SE (mol C m$^{-2}$ d$^{-1}$)</th>
<th>MNB</th>
<th>RMSE (mol C m$^{-2}$ d$^{-1}$)</th>
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5.2. Impacts of temperature and moisture on photosynthesis

A number of LUE models incorporate moisture and/or temperature as important environmental controls in plant photosynthesis (Prince & Goward, 1995; Running et al., 2004; Xiao, Hollinger, et al., 2004). Because GPP generally has a sigmoidal relationship with temperature (Fig. 8), the temperature equation (TEMP) developed for the Terrestrial Ecosystem Model (TEM) has proven effective in expressing the effect of temperature on photosynthesis (Raich et al., 1991). In the TEMP, minimum, maximum and optimal temperatures for photosynthetic activities are three necessary input parameters and are, therefore, important in GPP estimation. However, these three temperatures are derived from either ground observations or the literature, both of which limit the spatial application of TEMP-based GPP models. Furthermore, temperature primarily controls photosynthesis at the beginning and end of the growing season (Chen et al., 2005; Linkosalo, 2000; Yuan et al., 2007), which can be represented effectively by the EVI time series (Zhang et al., 2003). Thus, the PCM does not include temperature as a constraint. However, whether the PCM is effective in GPP estimation when the temperature is extremely high or low has not been examined because these conditions did not occur during the study period (Fig. 4).

Fig. 8. Plots of the observed GPP against air temperature ($T_a$), based on an 8-day average during the growing season. A: temperate mixed forest (CBS), B: temperate steppe (NM), C: alpine shrubland (HBGC), D: alpine marsh (HBSD), and E: alpine meadow-steppe (DX).
Although the observed GPP responds almost linearly to the moisture index during the growing season in each vegetation type (Fig. 9), the PCM does not perform well under conditions of serious drought (NM in 2005, Fig. 3B).

5.3. Application of the PCM at regional scale

The PCM can potentially be used in regional GPP estimation. The PCM follows Monteith’s (1972, 1977) logic and is entirely driven by the MODIS imagery. This approach avoids the introduction of substantial simulation errors into regional estimation due to the coarse spatial resolution of ground observations (Rahman et al., 2005; Sims et al., 2008; Wu, Niu, & Gao, 2010; Yang et al., 2007). The model parameter (PCmax) has a clear ecological meaning and is linearly correlated with the mean annual nighttime LST retrieved from MODIS imagery. Using this linear equation, Eq. (15), to replace the PCmax in the PCM, the PCM-simulated GPP can explain 93% of the variation in the flux-observed GPP across all five vegetation types (Fig. 10). Furthermore, with the development of remote sensing techniques and algorithms related to canopy chlorophyll content and moisture conditions, the PCM is promising to provide more accurate estimates of GPP.

6. Conclusions

This study developed a MODIS-based Photosynthetic Capacity Model (PCM) for simulating gross primary production (GPP) of terrestrial ecosystems in North China and the Tibetan Plateau. The PCM follows Monteith’s logic and is driven solely by the Enhanced Vegetation Index (EVI) and the Land Surface Water Index (LSWI) from MODIS imagery. The predictive accuracy of the PCM was higher than that of the MOD17 products and comparable with the VPM and the potential agery. The predictive accuracy of the PCM was higher than that of the Index (EVI) and the Land Surface Water Index (LSWI) from MODIS im-

Fig. 9. Plots of the observed GPP against moisture index (Wm) based on an 8-day average during the growing season. A: temperate mixed forest (CBS), B: temperate steppe (NM), C: alpine shrubland (HBSC), D: Alpine marsh (HBSD), and E: Alpine meadow-steppe (DX).

Fig. 10. Comparison between the flux-observed GPP and the PCM-simulated GPP, based on an 8-day average. The PCmax of the PCM was calculated from Eq. (15). Multi-year data from all five vegetation types are plotted in the figure. SE: coefficient of determination, SE: standard error of the simulated GPP (mol C m−2 d−1), MNB: mean normalized bias, RMSE: root mean square error (mol C m−2 d−1), and EF: modeling efficiency.

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References


