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# Attribute parameter characterized the seasonal variation of gross primary productivity ( $\alpha_{GPP}$ ): Spatiotemporal variation and influencing factors



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ABSTRACT

The seasonal dynamic of gross primary productivity (GPP) has influences on the annual GPP (AGPP) of the terrestrial ecosystem. However, the spatiotemporal variation of the seasonal dynamic of GPP and its effects on spatial and temporal variations of AGPP are still poorly addressed. In this study, we developed a parameter,  $\alpha_{GPP}$ , defined as the ratio of mean daily GPP (GPP<sub>mean</sub>) to the maximum daily GPP (GPP<sub>max</sub>) during the growing season, to analyze the seasonal dynamic of GPP based on Weibull function. The  $\alpha_{GPP}$  was a comprehensive parameter characterizing the shape, scale, and location of the seasonal dynamic curve of GPP. We calculated  $\alpha_{GPP}$  based on the data of GPP for 942 site-years from 115 flux sites in the Northern Hemisphere, and analyzed the spatiotemporal variation and influencing factors of the  $\alpha_{GPP}$ . We found that the  $\alpha_{GPP}$  of terrestrial ecosystems in the Northern Hemisphere ranged from 0.47 to 0.85, with an average of 0.62  $\pm$  0.06. The  $\alpha_{GPP}$  varied significantly both among different climatic zones and different ecosystem types. The  $\alpha_{GPP}$  was stable on the interannual scale, while decreased as latitude increased, which was consistent across different ecosystem types. The spatial pattern of the seasonal dynamic of astronomical radiation was the dominating factor of the spatial pattern of  $\alpha_{GPP}$ , that was, the spatial pattern of the seasonal dynamic of astronomical radiation determined that of the seasonal dynamic of GPP by controlling that of seasonal dynamics of total radiation and temperature. In addition, we assessed the spatial variation of AGPP preliminarily based on  $\alpha_{GPP}$  and other seasonal dynamic parameters of GPP, indicating that the understanding of the spatiotemporal variation of  $\alpha_{GPP}$  could provide a new approach for studying the spatial and temporal variations of AGPP and estimating AGPP based on the seasonal dynamic of GPP.

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#### 1. Introduction

Gross primary productivity (GPP) is an essential component of material and energy cycling in ecosystems that drives various ecosystem processes such as respiration and growth (Anav et al., 2015; Beer et al., 2010). The annual GPP (AGPP) of an ecosystem is the total amount of  $CO_2$  fixed by plants during photosynthesis within one year and is the largest carbon flux in an ecosystem (Beer et al., 2010; Ryan et al., 2017). Therefore, small changes in the AGPP can considerably alter the ecosystem carbon balance and may have consequences for atmospheric  $CO_2$  concentrations (Piao et al., 2009; Yao et al., 2018).

Seasonal variations of the supply of resources and environmental variables, such as temperature and water, affect plant phenology and then shape the unique seasonal dynamic of GPP in each climatic zone and various types of ecosystems (Allard et al., 2008; Falge et al., 2002a, 2002b; Gu et al., 2009; Hirata et al., 2007; Saigusa et al., 2008), finally determine the spatial and temporal variations in AGPP of ecosystems (Xia et al., 2015; Zhou et al., 2016). Therefore, to facilitate accurate assessments of the spatial and temporal variations in AGPP at regional and global scales, the seasonal dynamic of GPP need to be quantified (Falge et al., 2002a; Zhang et al., 2017).

Previous researchers have used a variety of classical functions (parabola, Weibull function, etc.) to describe the seasonal dynamic of GPP, and proposed a series of parameters to quantify the seasonal dynamic attributes of GPP (Gu et al., 2003, 2009). For example, the maximum value and amplitude describe the potential (GPPmax) and the magnitude of photosynthetic variation in the growing season; the length between growth initiation and termination can describe the length of active period of photosynthesis (CUP); skewness and rate of change can describe the degree of symmetry and steepness of the seasonal dynamic curve of GPP (Falge et al., 2002b; Gu et al., 2003, 2009; Xia et al., 2015). These parameters quantitatively describe the attributes of the seasonal dynamic of GPP, which is helpful to understand the seasonal dynamic of GPP and the formation process of AGPP, and also to compare and analyze the differences of seasonal dynamics of GPP between different climatic zones, different types of ecosystems and different interannual periods. They can also be related to climatic variables to reveal the impact of changes in climatic variables on spatial and temporal variations of AGPP (Gu et al., 2009; Niu et al., 2013; Richardson et al., 2010).

According to the seasonal dynamic of GPP, the annual GPP (AGPP) is the integral value of the daily GPP during the growing season, which can be expressed as the product of the growing season length (CUP) and the mean daily GPP ( $GPP_{mean}$ ) of the growing season. Then we defined a seasonal dynamic attribute parameter of GPP,  $\alpha_{GPP}$ , as the ratio of the mean daily GPP (GPP<sub>mean</sub>) to the maximum daily GPP (GPP<sub>max</sub>) during the growing season. Therefore, the AGPP can be expressed as the product of three seasonal dynamic attribute parameters of GPP (GPPmax,  $\alpha_{GPP}$ , CUP). Xia et al. had found that CUP and  $GPP_{max}$  could jointly control more than 90% of global AGPP variation based on observational data (Xia et al., 2015). Previous studies have shown that the CUP and GPP<sub>max</sub> were biogeographic attribute parameters determined by climatic variables (Hu et al., 2010; Jeong et al., 2011; Piao et al., 2006; Zhou et al., 2017), while  $\alpha_{GPP}$  was used as an empirical coefficient, and the characteristics and mechanism of spatiotemporal two-dimensional variation of  $\alpha_{GPP}$  were still not clear. Therefore, a more comprehensive understanding of spatial and temporal variations and environmental drivers of  $\alpha_{GPP}$  is needed to support more accurate assessments of global pattern in AGPP based on the seasonal dynamic of GPP.

In this study, observed flux data for 942 site-years of GPP were collected from 115 sites in the FLUXNET and ChinaFlux network. Parameters that described the seasonal dynamic of GPP (GPP<sub>mean</sub> and GPP<sub>max</sub>) were extracted and used to calculate the  $\alpha_{GPP}$  for each site-year. The specific aims of this study were: (1) to obtain the statistical characteristics of  $\alpha_{GPP}$  in different regions, (2) to reveal the



**Fig. 1.** The seasonal dynamic of GPP and accumulation of AGPP. The red curve indicates the seasonal dynamic of GPP; the black line is the cumulative curve of AGPP; the area of the shaded part indicates AGPP; the area of the yellow rectangular indicates the product of CUP and GPP<sub>max</sub>. AGPP is Annual Gross Primary Productivity; CUP is growing season length; GPP<sub>mean</sub> is mean daily GPP during CUP; GPP<sub>max</sub> is maximum daily GPP;  $\alpha_{GPP}$  is the ratio of GPP<sub>mean</sub> to GPP<sub>max</sub>. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

spatiotemporal variation and influencing factors of  $\alpha_{GPP}$ , (3) to discuss the mechanism and quantitative expression of spatiotemporal variation of  $\alpha_{GPP}$ , (4) to explore a new approach to assess the AGPP based on the spatiotemporal variation of  $\alpha_{GPP}$ .

#### 2. Material and methods

#### 2.1. Theoretical basis and definition of $\alpha_{GPP}$

The AGPP of an ecosystem can be defined as the sum of the daily GPP (GPP(t)) over the whole growing season (Fig. 1), which can be expressed as the product of CUP and GPP<sub>mean</sub>:

$$AGPP = \int GPP(t) dt = GPP_{mean} \times CUP$$
(1)

CUP in Eq. (1) was an ecological parameter depending on temperature, while  $\text{GPP}_{\text{mean}}$  was difficult to measure directly because of the complex forming mechanism. As  $\text{GPP}_{\text{max}}$  was relatively easy to measure, in this study, we used  $\text{GPP}_{\text{max}}$  to replace  $\text{GPP}_{\text{mean}}$  and convert Eq. (1) into Eq. (2) (Xia et al., 2015):

$$AGPP = \alpha_{GPP} \times GPP_{max} \times CUP$$
(2)

Here we defined the ratio of GPP<sub>mean</sub> to GPP<sub>max</sub> as  $\alpha_{GPP}$ , an attribute parameter characterizing the seasonal dynamic of GPP:

$$\alpha_{\rm GPP} = \frac{\rm GPP_{mean}}{\rm GPP_{max}} \tag{3}$$

We assumed that CUP and  $\text{GPP}_{max}$  could be quantified by climatic variables. Therefore, if we can quantitatively express the spatial pattern and interannual variation of  $\alpha_{\text{GPP}}$ , it is possible to develop a model to assess the spatial and interannual variations of AGPP in a large scale based on the spatiotemporal variation of the seasonal dynamic of GPP.

Previous studies have shown that as a phenological parameter of the ecosystem, CUP was mainly affected by temperature (Hu et al., 2010; Jeong et al., 2011; Piao et al., 2006). Therefore, CUP could be estimated by the functions of climatic indicators such as annual mean temperature (AMT), effective accumulated temperature, and other biological boundary temperature. GPP<sub>max</sub> was the maximum value that daily GPP of the ecosystem could achieve within a year, which could be calculated based on observation data of the flux and remote sensing, or climatic and plant variables. Thus,  $\alpha_{GPP}$  could also be expressed through a combination of CUP and GPP<sub>max</sub> as shown in Eq. (4):

It can be seen from Eq. (4) and Fig. 1 that  $\alpha_{GPP}$  was a mathematical parameter characterizing the geometry of the seasonal dynamic curve of GPP. The ecophysiological significance of  $\alpha_{GPP}$  was the ratio of the area of seasonal dynamic curve in GPP to the area of a rectangle with the length CUP and the height GPP<sub>max</sub>. Thus, if we can quantitatively express  $\alpha_{GPP}$ , the Eq. (2) can be used as a universal biogeographic model to estimate the spatiotemporal two-dimensional variation of AGPP.

The seasonal pattern of GPP is relatively stable in a relatively stable climate condition (Falge et al., 2002b; Gu et al., 2009), which is controlled by the seasonal dynamics of total radiation and temperature (Barr et al., 2009). We can assume that the biogeographic mechanism of spatiotemporal variation of  $\alpha_{GPP}$  is that the spatiotemporal pattern of the seasonal dynamic of astronomical radiation affected the spatiotemporal pattern of the seasonal dynamics of climatic variables. This study aims to prove the mechanism and explore the approach to the application of this mechanism in the assessment of the spatiotemporal variation of AGPP.

#### 2.2. Data sources

#### 2.2.1. Source of GPP data

The eddy covariance method provides a direct measure of carbon fluxes between vegetation and the atmosphere over a range of timescales (hour, day, month, and year), thereby providing datasets for studies of the temporal dynamics of GPP (Baldocchi, 2003, 2008; Baldocchi et al., 2001; Xu and Baldocchi, 2004; Yu et al., 2006). The GPP data used in this study were obtained from the Fluxnet 2015 (www.fluxdata.org) and ChinaFlux (www.chinaflux.org) datasets. The Fluxnet 2015 and China-Flux datasets were both standardized by uniform methods. The halfhourly data of NEE (Net Ecosystem Exchange) from the Fluxnet 2015 dataset were gap-filled using the marginal distribution sampling (MDS) method (Reichstein et al., 2005), and partitioned into GPP and ecosystem respiration based on nighttime data (Reichstein et al., 2005) or daytime data (Lasslop et al., 2010). In this study, we used GPP data partitioned based on nighttime data. The half-hourly data of NEE in ChinaFlux dataset were gap-filled using nonlinear regression methods (Falge et al., 2001) and partitioned into GPP and ecosystem respiration based on nighttime data (Reichstein et al., 2005; Yu et al., 2013).

The data used in this study from the Fluxnet 2015 and ChinaFlux datasets met the following three criteria: (1) more than 75% of the GPP data for the site-year were reliable and the data covered the whole growing season; (2) the sites had at least 3 site-years of data, and (3) data were for natural ecosystems only, including forest, grassland, wetland, and shrubland. Cropland ecosystems were not included because of the disturbance caused by intensive human activities.

After being filtered by these criteria, GPP data for 942 site-years from 115 sites were included in this study (Fig. 2). More details of the sites were provided in Appendices Table A.1. These sites covered 8 ecosystem types, namely deciduous broad-leaved forests (DBF, 18 sites), deciduous-coniferous forest (DNF, 1 site), evergreen broad-leaved forests (EBF, 9 sites), evergreen coniferous forests (ENF, 34 sites), mixed forests (MF, 8 sites), grasslands (24 sites), wetlands (13 sites), and shrublands (8 sites), and were distributed across tropical (4 sites), subtropical (6 sites), Mediterranean (18 sites), temperate (16 sites), continental (56 sites), polar and alpine (9 sites), and arid (6 sites) climatic zones.

In addition, the interannual variability in  $\alpha_{GPP}$  was quantified from data for 33 sites that had continuous measurements for more than 10 years. Of these 33 sites, 23 had data between 10 and 15 years, 9 had data between 16 and 20 years, and 1 had data for 21 years. These 33 flux sites were classified into DBF (8 sites), EBF (3 sites), ENF (12 sites),



Fig. 2. Distribution of flux sites in this study. Dots indicate the flux sites, and triangle points indicate 33 sites for the analysis of interannual variations.

MF (4 sites), grassland (5 sites), and wetland (1 site) ecosystems, and were distributed across the tropical (2 sites), subtropical (2 sites), Mediterranean (1 site), temperate (7 sites), continental (16 sites), polar and alpine (4 sites), and arid (1 site) climatic zones.

## 2.2.2. Data for climatic variables

We analyzed temperature, precipitation, and total radiation (downward shortwave radiation) data for the same period as the flux observation from the Fluxnet 2015 and ChinaFlux datasets, which were standardized using Fluxnet and ChinaFlux methods. The half-hourly data in the Fluxnet 2015 dataset were gap-filled using the MDS method (Reichstein et al., 2005). For some sites, the meteorological data were downscaled at the site level from the ERA-interim reanalysis data following the method described by Vuichard and Papale (2015). A proposed optimal combination of meteorological data of these two methods was also produced. We used the optimal combination of the two methods in this study. The data in the ChinaFlux dataset were gapfilled using the mean diurnal variation (MDV) method (Yu et al., 2006).

The astronomical radiation (the solar radiation in the upper boundary of the Earth's atmosphere determined by the astronomical position between the sun and the earth) for each site in each day was calculated using the formula (Eq. (5), Yu and Sun, 2006) for astronomical radiation.

$$Q = \frac{\mathrm{TI}_0}{\pi \rho^2} (\omega_0 \mathrm{sin}\varphi \mathrm{sin}\delta + \mathrm{cos}\varphi \mathrm{cos}\delta \mathrm{sin}\omega_0)$$
(5)

 $\rho^{2} = \frac{1}{1.000109 + 0.033494\cos\theta + 0.001472\sin\theta + 0.000768\cos2\theta + 0.000079\sin2\theta}$  $\delta = 0.006894 - 0.399512\cos\theta + 0.070257\sin\theta - 0.006799\cos2\theta + 0.000896\sin2\theta$ (6)

$$-0.002689\cos 3\theta + 0.001516\sin 3\theta$$
 (7)

$$\omega_0 = \arccos(-\tan\varphi \times \tan\delta) \tag{8}$$

$$\theta = \frac{2\pi(n-1)}{365} \tag{9}$$

where *Q* was the daily astronomical radiation in a specific latitude; *T* was the length of one day,  $T/\pi = 458.4$ ;  $I_0$  was the solar constant (1367 W m<sup>-2</sup>);  $\rho$  was the relative distance from the earth to the sun (the ratio of the distance between the sun and the earth at a certain moment to the mean radius of the Earth's orbit, Eq. (6), Zuo et al., 1991);  $\delta$  was the declination (angular distance north or south from the celestial equator measured along a great circle passing through the celestial poles, Eq. (7), Zuo et al., 1991);  $\omega_0$  was the hour angle (the angular distance on the celestial sphere measured westward along the celestial equator from the meridian to the hour circle passing through a point, Eq. (8), Yu and Sun, 2006);  $\phi$  was the latitude, and *n* was the day of the year.

#### 2.3. Extracting the seasonal dynamic parameters

#### 2.3.1. Extracting the seasonal dynamic parameters of GPP

The seasonal patterns in GPP vary across ecosystems and regions in the Northern Hemisphere terrestrial ecosystems. Seasonal patterns in GPP can be categorized into three types, as follows: (1) typical unimodal mode; (2) multiple peaks, and (3) growing throughout the whole year (Xia et al., 2015). Different methods were used to fit the curves and extract the seasonal dynamic parameters of GPP.

## (1) Typical unimodal mode:

Ecosystems of this type accounted for 84.35% of all sites, and were mainly distributed in the temperate zone and further north with the synchronous hydrothermal conditions. For these ecosystems, the fiveparameter Weibull function was used to fit the daily GPP data for each site-year (Xia et al., 2015) (Eq. (10)):

$$GPP(t) = \begin{cases} y_0 + \eta \left(\frac{k-1}{k}\right)^{\frac{1-k}{k}} \left| \frac{t-x_0}{\lambda} + \left(\frac{k-1}{k}\right)^{\frac{1}{k}} \right|^{k-1} e^{\left(-\left|\frac{t-x_0}{\lambda} + \left(\frac{k-1}{k}\right)^{\frac{1}{k}}\right|^k + \frac{k-1}{k}\right)} &, t > x_0 - \lambda \frac{k-1}{k} \\ y_0 &, t \le x_0 - \lambda \frac{k-1}{k} \end{cases}$$

where *GPP(t)* was the daily GPP (g C m<sup>-2</sup>d<sup>-1</sup>), *t* was the day of the year,  $\lambda$ ,  $\eta$ , *k*,  $x_0$ ,  $y_0$  were empirical parameters.  $\lambda$  was the scale parameter of x-axis;  $\eta$  was the scale parameter of y-axis; *k* was the shape parameter;  $x_0$  was the location parameter in x-axis;  $y_0$  was the location parameter of the y-axis.

And  $\ensuremath{\mathsf{GPP}_{\mathsf{max}}}$  was the maximum value of the daily  $\ensuremath{\mathsf{GPP}}$  over the whole year:

$$GPP_{max} = max\{GPP(t)\}$$
(11)

CUP was the number of days between  $\text{CUP}_{\text{start}}$  and  $\text{CUP}_{\text{end}}$ . In this study,  $\text{CUP}_{\text{start}}$  was defined as the intersection between the recovery line (representing the maximum growth rate of GPP) and the time axis (day of the year), and the  $\text{CUP}_{\text{end}}$  was defined as the intersection between the senescence line (representing the minimum growth rate of GPP) and the time axis (day of the year) (Xia et al., 2015). CUP was calculated as Eq. (12):

$$CUP = CUP_{end} - CUP_{start}$$
(12)

So the GPP<sub>mean</sub> can be calculated as:

$$GPP_{mean} = \frac{AGPP}{CUP}$$
(13)

#### (2) Multiple peaks:

Ecosystems of this type accounted for 10.43% of all sites, and were mainly distributed in the Mediterranean climatic zone with the asynchronous hydrothermal conditions. For multiple peaks, each peak was taken to represent a single growing season, and then the results of each growing season were weighed to calculate the annual CUP and GPP<sub>max</sub>, and the GPP<sub>mean</sub> was calculated according to Eq. (13). Further details about the curve fitting and parameter extraction methods can be found in Xia et al. (2015).

## (3) Growth throughout the whole year:

Ecosystems of this type accounted for 5.22% of all sites, and were mainly distributed in the low latitude with little variation of climatic variables. GPP in this type was smoothed using a moving average method with the 7-day time window. As the growing season for this type persisted over the year, CUP was 365 or 366 for a leap year, so the GPP<sub>mean</sub> was AGPP/365(or 366), and GPP<sub>max</sub> was the maximum value during the whole year (Eq. (11)).

Then  $\alpha_{GPP}$  of these three types were calculated with Eq. (3).

(10)

2.3.2. Extracting the seasonal dynamic parameters of the climatic variables We then extracted the seasonal dynamic parameters of climatic variables, including the astronomical radiation, temperature, and total radiation, using the method applied to  $\alpha_{GPP}$ . We extracted the mean and the maximum values of temperature when the daily mean temperature was above 0 °C, the mean and the maximum values of astronomical radiation when the daily astronomical radiation was above 0 W m<sup>-2</sup>, and the mean and the maximum values of total radiation when the daily

total radiation was above 0 W m<sup>-2</sup>. Then  $\alpha_Q$ ,  $\alpha_T$ , and  $\alpha_R$  were calculated as the ratio of the mean value to the maximum value of astro-

nomical radiation, temperature, and total radiation, respectively.

#### 2.4. Statistical analysis

The  $\alpha_{GPP}$  in any location at a given year (marked as  $\alpha_{Gij}$ ) was the combination of its spatial and interannual variations, and could be split into spatial and interannual components to analyze the spatial and

temporal variations, respectively:

$$\alpha_{Gij} = \alpha_{Gi} + \Delta \alpha_{Gij}; \quad i = 1, 2...m, j = 1, 2...n$$
(14)

$$\alpha_{Gi} = \frac{1}{n} \sum_{j=1}^{n} \alpha_{Gij} = \frac{1}{n} \sum_{j=1}^{n} \left( \frac{\text{GPP}_{meanij}}{\text{GPP}_{maxij}} \right); \quad i = 1, 2...m$$
(15)

$$\Delta \alpha_{Gij} = \alpha_{Gij} - \alpha_{Gi}; \quad i = 1, 2...m, j = 1, 2...n$$
(16)

where  $\alpha_{Gij}$  was the  $\alpha_{GPP}$  in a specific site for a given year, *i* was the site, *j* was the year, *n* was the number of years in this site, *m* was the number of sites.  $\alpha_{Gi}$  was the mean value of  $\alpha_{Gij}$  for a specific site, and represented the spatial component of  $\alpha_{GPP}$ , and so the variation in  $\alpha_{Gi}$  characterized the spatial variation in  $\alpha_{GPP}$ .  $\Delta \alpha_{Gij}$  was the difference among multiple years at a specific site, and represented the interannual component of  $\alpha_{GPP}$ .

Similar to  $\alpha_{GPP}$ , the spatial components of annual mean temperature (AMT), annual total precipitation (ATP), annual total radiation (ATR), and annual total astronomical radiation (ATQ) were calculated as  $AMT_{i}$ ,  $ATP_{i}$ ,  $ATR_{i}$  and  $ATQ_{i}$ , and the spatial components of seasonal dynamic parameters of temperature ( $\alpha_{T}$ ), total radiation ( $\alpha_{R}$ ), and astronomical radiation ( $\alpha_{Q}$ ) were calculated as  $\alpha_{Ti}$ ,  $\alpha_{Ri}$  and  $\alpha_{Qi}$ .

A non-parametric test followed by the Tamhane's T2 test with a significance level of 0.05 was used to determine whether there were significant differences among different climatic zones and ecosystem types. The relationships between the variations in  $\alpha_{GPP}$  and latitude, and between the climatic variables and  $\alpha_{Gi}$  were examined with linear regression.

Path analysis was designed to assess the influences of spatial components of climatic variables on the spatial component of  $\alpha_{GPP}$ . The autocorrelation coefficient of time series was used to determine whether the interannual variation of  $\alpha_{GPP}$  was weak stationary (Kendell et al., 1983; Sun et al., 2018), and the coefficient of variation was then used to quantitatively describe the interannual variability of  $\alpha_{GPP}$  (Bai et al., 2004; Ganguly et al., 2010; Reed et al., 2002). The autocorrelation coefficient of a time series refers to the correlation of two values in the same dataset at different time steps (Cryer and Kellet, 1991). With the increase in the number of lag years (i.e., the phase difference between two different periods of the time series), the autocorrelation coefficients of a weak stationary time series decrease rapidly to zero (Sun et al., 2018). Moreover, if the autocorrelation coefficients of a time series fall within two times of the standard deviations, the time series can be considered to be stationary (Cryer and Kellet, 1991). In this study, the autocorrelation coefficients and two times standard deviations of lags from 1 year to n-4 years (n was the number of years) for each site with continuous data over a decade were calculated in MATLAB 2012a with 'autocorr' function. Coefficient of variation can be calculated as Eq. (17):

$$CV = \frac{SD}{Mean} \times 100\%$$
(17)

where CV was the coefficient of variation, SD was standard deviation, Mean was the average value.

#### 3. Results

## 3.1. Statistical characteristics and variability in $\alpha_{GPP}$

The  $\alpha_{GPP}$  of 942 site-years in the Northern Hemisphere varied from 0.47 to 0.85 with an average of 0.62  $\pm$  0.06 and a CV of 9.35%.

The  $\alpha_{GPP}$  varied significantly among different climatic zones (P < 0.05) (Table 1). The mean  $\alpha_{GPP}$  in all climatic zones ranged from 0.60 to 0.79. The mean  $\alpha_{GPP}$  in the tropical zone was largest, followed by subtropical, and Mediterranean zones. The mean  $\alpha_{GPP}$  values for the subtropical and Mediterranean zones were significantly higher than those for other climatic zones except tropics (P < 0.05). The mean  $\alpha_{GPP}$  value for the continental zone was significantly lower than other climatic zones. There was no significant difference of  $\alpha_{GPP}$  among temperate, polar and alpine, and arid zones. The coefficient of variation (CV) of  $\alpha_{GPP}$  was largest in the Mediterranean climatic zone (9.42%) and was lowest in the tropics (4.85%) (Table 1).

When examined by ecosystem type (Table 2), the  $\alpha_{GPP}$  was highest for EBF, which was significantly higher than other types; the mean values of  $\alpha_{GPP}$  in DBF and wetland were significantly lower than that of grassland, shrubland, and EBF; and there was no significant difference among  $\alpha_{GPP}$  for ENF, MF, grassland and shrubland. The CV values of  $\alpha_{GPP}$  ranged from 3.28% to 8.33%, and the CV values for DBF and wetland were largest (Table 2).

The regression results showed that the spatial component,  $\alpha_{Gb}$  accounted for 70% of the variation in  $\alpha_{GPP}$  (Fig. 3a), while the interannual component,  $\Delta \alpha_{Gij}$ , accounted for 30% (Fig. 3b). The variation in the  $\alpha_{GPP}$  was mostly attributable to spatial variation.

## 3.2. Interannual variability in $\alpha_{GPP}$

There was a low-amplitude irregular fluctuation both in  $\alpha_{Gij}$  and the interannual component of  $\alpha_{Gij}$ ,  $\Delta \alpha_{Gij}$ , and the  $\alpha_{Gij}$  was relatively stable between years. There were no significant trends or periodicity in  $\alpha_{Gij}$  over the years (Fig. 4a–c). Even in the tropical, Mediterranean, and continental zones with larger fluctuation of  $\alpha_{Gij}$ , there were no significant interannual trends. There were no significant trends or periodicity in the  $\Delta \alpha_{Gii}$  (Fig. 4d–f). More than 94% of the  $\Delta \alpha_{Gii}$  values were

#### Table 1

Statistical characteristi	ics of	$\alpha_{GPP}$	in	different	climatic	zones
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Climatic zones	Mean	Range of variation	95% Confidence interval	CV(%)
Tropical Subtropical Mediterranean Temperate Continental Polar and alpine	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	0.69–0.85 0.60–0.78 0.54–0.80 0.55–0.79 0.47–0.77 0.49–0.72	0.77-0.80 0.66-0.68 0.65-0.68 0.61-0.62 0.60-0.61 0.61-0.63	4.85 5.82 9.42 6.71 7.16 6.62
Aria	$0.62 \pm 0.04^{\circ}$	0.53-0.71	0.01-0.04	5.63

The letters a, b, c, and d represent the results of the non-parametric test. Different letters indicate the significant differences between zones, and the same letter indicates that there is no significant difference.

Table 2							
Statistical	characteristics	of	$\alpha_{GPP}$	in	different	ecosystem	types.

$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Ecosyst	em types	Mean	Range of variation	95% Confidence interval	CV(%)
$Silfuplating 0.04 \pm 0.05 = 0.47 - 0.74 = 0.02 - 0.05 = 7.81\%$	Forest	DBF DNF EBF ENF MF Grassland Wetland Shrubland	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	0.52-0.80 0.59-0.63 0.61-0.85 0.48-0.80 0.55-0.74 0.50-0.79 0.48-0.69 0.47-0.74	0.59-0.60 0.56-0.66 0.71-0.75 0.61-0.63 0.61-0.63 0.62-0.63 0.59-0.61 0.62-0.65	8.33% 3.28% 8.22% 8.06% 6.45% 7.94% 8.33% 7.81%

The letters a, b and c indicate the difference detected by the non-parametric test. Different letters indicate that there are significant differences between ecosystems, and the same letter indicates that there is no significant difference between ecosystems. It should be noted that there was only one site of DNF, so we only listed the statistical value of this type, and did not analyze the difference between DNF and other ecosystem types.

#### between -0.06 and 0.06.

The autocorrelation coefficient tended to decrease rapidly towards zero as the number of lag years increased, and the autocorrelation coefficients in 94% of sites were all within two times of standard deviations (Fig. A1). The results of autocorrelation coefficient in each site indicated that  $\alpha_{Gij}$  was weak stationary between years, that was,  $\alpha_{Gij}$  did not increase or decrease with years, nor did it fluctuate with regular periodicity, but fluctuated around a constant value.

The CV exceeded 10% at only one site (US-GLE), where it was 12%; otherwise, 76% of the CVs of the interannual variation in  $\alpha_{GPP}$  was less than 5% (Fig. A2). The results of CV further indicated that the interannual variation of  $\alpha_{GPP}$  was small and could be regarded as weak stationary.

## 3.3. Spatial pattern and influencing factors of $\alpha_{GPP}$

#### 3.3.1. Spatial pattern of $\alpha_{GPP}$

The  $\alpha_{GPP}$  in the Northern Hemisphere terrestrial ecosystems decreased significantly as latitude increased (Fig. 5a). From the equator to 75°N,  $\alpha_{GPP}$  decreased from 0.85 to 0.5. The spatial component,  $\alpha_{Gi}$ , also showed a tendency to decrease as the latitude increased (Fig. 5b). From the equator to 75°N,  $\alpha_{Gi}$  decreased from 0.85 to 0.55. At different latitudes,  $\alpha_{Gi}$  decreased at different rates. The rate of decrease in  $\alpha_{Gi}$  was 0.15 between 0° and 30°N, and was 0.10 from 30°N to 75°N.

The  $\alpha_{Gi}$  decreased with increasing in latitude for all ecosystem types (Fig. 5b), with significant decreasing trends for DBF, ENF, and shrubland. Within the latitude ranges of each type, the  $\alpha_{Gi}$  decreased by 0.18, 0.16, 0.21, 0.08, 0.14, 0.11 and 0.12 in DBF, EBF, ENF, MF, grassland, wetland and shrubland, respectively. For every 10° increased in latitude, the  $\alpha_{Gi}$  decreased by 0.04, 0.02, 0.02, 0.02, 0.01, 0.01, and 0.02, respectively (Fig. 5b).

## 3.3.2. Factors affecting spatial pattern of $\alpha_{GPP}$

Previous studies have proved that the spatial pattern of AGPP was affected by climatic variables such as annual mean temperature (AMT), annual total precipitation (ATP) and annual total radiation (ATR) (Chen et al., 2013, 2015; Hirata et al., 2008; Law et al., 2002; Luyssaert et al., 2007; Yu et al., 2013; Zhu et al., 2016). There were also significant correlations between the spatial components of the three climatic variables ( $AMT_i$ ,  $ATP_i$ , and  $ATR_i$ ) and  $\alpha_{Gi}$  (P < 0.001) (Fig. A3a–c). The  $\alpha_{Gi}$  was most strongly correlated with  $AMT_i$  ( $r^2 = 0.31$ ), followed by  $ATP_i$  ( $r^2 = 0.19$ ), and  $ATR_i$  ( $r^2 = 0.10$ ). Further analysis by path analysis showed that the spatial component of annual total astronomical radiation ( $ATQ_i$ ) affected the spatial component of seasonal dynamic of GPP through its influence on the spatial components of annual total radiation ( $ATR_i$ ), annual mean temperature ( $AMT_i$ ), and annual total precipitation ( $ATP_i$ ) (Fig. 6a).



Fig. 3. Relationships between  $\alpha_{GPP}$  and (a) the spatial component  $\alpha_{Gi}$  and (b) the interannual component  $\Delta \alpha_{Gij}$ .



**Fig. 4.** Interannual variation in  $\alpha_{Gij}$  (a–c) and its interannual component  $\Delta \alpha_{Gij}$  (d–f) at each site. Each polyline represents a site; the red lines in (d), (e), and (f) indicated one standard deviation (1\*sd = 0.06). (a) and (d) represent the interannual variations of (a)  $\alpha_{Gij}$  and (d)  $\Delta \alpha_{Gij}$  in the tropical, subtropical, Mediterranean and arid climatic zones; (b) and (e) represent the interannual variations of (b)  $\alpha_{Gij}$  and (e)  $\Delta \alpha_{Gij}$  in the temperate and polar and alpine climatic zones; (c) and (f) represent the interannual variations of (c)  $\alpha_{Gij}$  and (f)  $\Delta \alpha_{Gij}$  in the continental zones. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 5.** The spatial pattern in (a)  $\alpha_{Gij}$  and (b)  $\alpha_{Gi}$   $\alpha_{Gi}$  is the spatial component of  $\alpha_{Gij}$ , different colors represent different ecosystem types, \*\*\* indicates P < 0.01; \*\* indicates P < 0.05; \* indicates P < 0.1.



**Fig. 6.** Influence of environmental variables on  $\alpha_{Gi}$ . The numbers in the figure indicate the correlation between two variables, and \*\*\* indicates P < 0.01; \* indicates P < 0.1;  $ATQ_i$ ,  $ATR_i$ ,  $AMT_i$ , and  $ATP_i$  are the spatial components of annual total astronomical radiation, annual total radiation, annual mean temperature, and annual total precipitation;  $\alpha_{Qi}$ ,  $\alpha_{Tb}$ ,  $\alpha_{Ri}$  and  $\alpha_{Gi}$  are the spatial components of the seasonal dynamics parameter of astronomical radiation, temperature, total radiation and GPP.

We then analyzed the effects of the spatial components of seasonal dynamic parameters of astronomical radiation ( $\alpha_{Qi}$ ), mean temperature ( $\alpha_{Ti}$ ), and total radiation ( $\alpha_{Ri}$ ) on  $\alpha_{Gi}$ . The results showed that  $\alpha_{Tb}$   $\alpha_{Ri}$ , and  $\alpha_{Qi}$  had significant effects on the spatial pattern of  $\alpha_{Gi}$  (P < 0.001) (Fig. A3d–f). The  $\alpha_{Gi}$  was most strongly correlated with  $\alpha_{Qi}$  ( $r^2 = 0.33$ ), followed by  $\alpha_{Ti}$  ( $r^2 = 0.28$ ), and  $\alpha_{Ri}$  ( $r^2 = 0.26$ ).

The result of path analysis showed that the seasonal dynamic of astronomical radiation was the main climatic variable affecting the seasonal dynamic of GPP. It affected the seasonal dynamic of GPP by affecting the seasonal dynamics of total radiation and temperature (Fig. 6b). The indirect effect of  $\alpha_{Qi}$  on  $\alpha_{Gi}$  by  $\alpha_{Ri}$  was 0.26, which was larger than that of  $\alpha_{Qi}$  on  $\alpha_{Gi}$  via  $\alpha_{Ti}$  (0.20).

#### 3.3.3. Quantitative description of the spatial pattern of $\alpha_{GPP}$

According to the theoretical formula of astronomical radiation (Eq. (5)), the astronomical radiation of a certain day in the ecosystem is determined by latitude where the ecosystem located in. Therefore, the seasonal dynamic attribute parameter  $\alpha_Q$  of the astronomical radiation is also determined by latitude. Since  $\alpha_{Qi}$  is the main factor affecting  $\alpha_{Gi}$ , the relationship between  $\alpha_{Qi}$  and  $\alpha_{Gi}$  can be expressed by the relationship between latitude and  $\alpha_{Gi}$  (Fig. 7).

Based on this relationship, we developed an empirical equation (Eq. (18)) to quantitatively express how  $\alpha_{Gi}$  varied with latitude:

$$\alpha_{Gi} = 3.72 \times 10^{-5} \times \varphi^2 - 0.0056 \times \varphi + 0.8009 \tag{18}$$

where  $\varphi$  was the altitude. The latitude could explain 36% of the variation of  $\alpha_{Gi}$ .



**Fig. 7.** The relationships between  $\alpha_{Gi}$  and latitude.  $\alpha_{Gi}$  is the spatial component of  $\alpha_{GPP}$ .

#### 4. Discussion

## 4.1. Ecological significance of $\alpha_{GPP}$

The different seasonal dynamics of GPP in different climatic zones are controlled by the seasonal dynamics of climatic variables such as radiation, temperature, and precipitation. The seasonal dynamics of GPP can be described by different types of functions, the parameters characterizing these functions could be used as ecological attribute parameters for quantitative analysis of the seasonal dynamic of GPP. In this study, we used the five-parameter Weibull function (Gu et al., 2003, 2009; Xia et al., 2015) to describe the seasonal dynamics of GPP in different ecosystems. The five empirical parameters ( $\lambda$ ,  $\eta$ ,  $x_0$ ,  $y_0$ , k) in the function could comprehensively describe the geometric characteristics of the seasonal dynamic curve of GPP, where  $\lambda$  (Fig. A4a) and  $\eta$ (Fig. A5a) are the scale parameters in the x-axis and y-axis directions respectively, k (Fig. A6a) is the shape parameter,  $x_0$  (Fig. A4b) and  $y_0$ (Fig. A5b) are the location parameters in the x-axis and y-axis directions respectively.

As a scale parameter,  $\lambda$  could be used to characterize the steepness of increasing and decreasing processes of daily GPP. When it changes, the curve is stretched or compressed in the x-axis direction, and the days when maximum growth rate and senescence rate occur change (Fig. A4a), i.e., the time when the maximum value of the first derivative (Fig. A4c) and the zero value of the second derivative (Fig. A4e) occur changes. As a local parameter, the change of  $x_0$  only leads to the movement of the curve in the x-axis direction, and not affect the shape of curve (Fig. A4b), which causes the changes of the start and end days of the growing season, the day when daily GPP reaches the maximum value, and the days when the maximum growth rate and senescence rate occur (Fig. A4d and f).

Eq. A1 shows that the sum of  $y_0$  and  $\eta$  could represent the GPP<sub>max</sub> of the seasonal dynamic of GPP. As a location parameter, the change of  $y_0$  only leads to the movement of the curve in the y-axis direction, and not affect the periods when daily GPP increases and decreases (Fig. A5d and f). Thus, the  $y_0$  could be defined as the basic GPP (marked as GPP<sub>c</sub>) of the ecosystems. And  $\eta$ , the scale parameter in the y-axis direction, could be taken as the net variation of GPP<sub>max</sub>, i.e.,  $\eta = \text{GPP}_{max} - \text{GPP}_{c}$ . When  $\eta$  changes, the curve is stretched or compressed in the y-axis direction (Fig. A5a). The days when maximum growth rate and senescence rate occur do not change with the variation of  $\eta$  (Fig. A5a, e), but the values of maximum growth rate and senescence rate change (Fig. A5c).

As the shape parameter, k reflects the proportional relationship between the x-axis and the y-axis (Fig. A6a and Eq. (A18). When k changes, the curve shapes of GPP, the first derivative of GPP, and the second derivative of GPP are significantly changed (Fig. A6a–c), that is, the curve shape of the rate of change of GPP also changes (Fig. A6b).



**Fig. 8.** Seasonal dynamics (a, c, e, g, i, k, m) and rate of change of GPP and cumulative curves of AGPP (b, d, f, h, j, l, n) in different climatic zones. AGPP is Annual Gross Primary Productivity; CUP is growing season length; GPP<sub>mean</sub> is mean daily GPP during CUP; GPP<sub>max</sub> is maximum daily GPP;  $\alpha_{GPP}$  is the ratio of GPP<sub>mean</sub> to GPP<sub>max</sub>; R<sub>max</sub> is maximum growth rate of GPP; R<sub>min</sub> is maximum senescence rate of GPP.



Fig. 9. Seasonal variations in (a) GPP, (b) astronomical radiation, and (c) temperature at different latitudes.

In summary, the differences between the seasonal dynamics of GPP in different climatic zones and between different years were actually the differences between the parameters characterizing the functions fitting the seasonal dynamics of GPP. The  $\alpha_{GPP}$ , defined as the ratio of GPP<sub>mean</sub> to GPP<sub>max</sub> during the growing season, was a comprehensive parameter including five parameters characterizing the geometry of Weibull function. Actually,  $\alpha_{GPP}$  reflected the ratio of the area of seasonal dynamic curve in GPP to the area of a rectangle with the length CUP (CUP =  $t_2 - t_1$ ) and the height GPP<sub>max</sub> (GPP<sub>max</sub> =  $y_0 + \eta$ ) (Eq. (4) and Fig. 1), where the seasonal dynamic of GPP was affected by environmental variables and plant phenology, and  $\alpha_{GPP}$  was an important attribute parameter describing the seasonal dynamic of GPP.

The spatial pattern of  $\alpha_{GPP}$  could quantitatively express the spatial variation of seasonal dynamics of GPP and the formation process of AGPP (Fig. 8).

Firstly, in the tropics, where the climatic variables can meet the needs of plant growth over the whole year, the plant grows throughout the whole year (CUP = 365), the basic GPP (GPP<sub>c</sub>) is the largest, and the net variation of GPP<sub>max</sub> is the smallest (Fig. 8a). The daily GPP during the growing season remains almost a constant (Falge et al., 2002a) (Fig. 8a). As a result, the cumulative curve of AGPP approximates to a straight line and the rate of change in GPP is small (Fig. 8b). Therefore, the difference between GPP<sub>mean</sub> and GPP<sub>max</sub> is small, and  $\alpha_{GPP}$  is the largest (Fig. 8a).

Secondly, in the subtropics, although the temperature and precipitation generally meet the requirements for plant growth throughout the whole year, the GPP<sub>c</sub> is smaller than that in the tropics (Fig. 8c). In addition, because of the seasonal variations in the climatic variables, the variation of daily GPP in the growing season and the net variation of GPP<sub>max</sub> are both larger than those in the tropics (Fig. 8c), so that the cumulative curve of AGPP no longer follows a straight line (Fig. 8d). The rate of change in GPP shows a significant peak and trough, where a positive rate of change indicates the increase of GPP and a negative rate indicates the decrease of GPP (Fig. 8d). Therefore, the difference between GPP<sub>mean</sub> and GPP<sub>max</sub> in this zone increases so that the  $\alpha_{GPP}$  is significantly smaller than that in the tropics (Fig. 8c).

Thirdly, in the middle and high latitudes, from temperate zone to polar and alpine zone, the growing season length gradually becomes shorter with the increase of latitude, and the variation of daily GPP in the growing season further increases, so that the seasonal dynamic curve of GPP follows a unimodal form (Falge et al., 2002a) (Fig. 8g, i, k). Moreover, with the increase of latitude, the GPP<sub>max</sub> and the net variation of GPP<sub>max</sub> decrease, and the GPP<sub>c</sub> decreases towards zero (Fig. 8g, i, k). Therefore, the difference between GPP<sub>mean</sub> and GPP<sub>max</sub> increases, and the  $\alpha_{GPP}$  decreases (Fig. 8g, i, k), so that the cumulative curve of AGPP is increasingly consistent with the classical Logistic curve (Fig. 8h, j, l). However, although both GPP<sub>max</sub> and GPP<sub>mean</sub> decrease with increasing latitude, the difference between them varies little with latitude, so the  $\alpha_{GPP}$  decreases little with the increase of

latitude (Fig. 8g, i, k).

Finally, because of the asynchronous distribution of temperature and precipitation in the Mediterranean climatic zone, the peak of the seasonal dynamic curve of GPP skews to the left (Fig. 8e), indicating that the peak appears earlier than in other climatic zones. The cumulative curve of AGPP is not a straight line, and similar to that in subtropical zones (Fig. 8f). In the arid zone, due to the limitation of water, GPP is lower, and the difference between GPP<sub>mean</sub> and GPP<sub>max</sub> is larger, so the  $\alpha_{GPP}$  is smaller (Fig. 8m), and the cumulative curve of AGPP is similar to a logistic curve (Fig. 8n).

#### 4.2. Climatic controls on the spatiotemporal variation in $\alpha_{GPP}$

This study demonstrated our assumption of the biogeographic mechanism of spatial and interannual variation of  $\alpha_{GPP}$ . The mechanism can be described as "The spatiotemporal pattern of the seasonal dynamic of astronomical radiation determined the spatial and interannual patterns of the seasonal dynamic of GPP by controlling that of seasonal dynamics of climatic variables". Moreover, the spatiotemporal variation of the seasonal dynamic of GPP affected the spatial and interannual variations of AGPP. The similarities between the spatial patterns of the seasonal dynamic of GPP (Fig. 9a) and seasonal dynamics of astronomical radiation and temperature (Fig. 9b, c) further proved this mechanism.

Astronomical radiation is the main source of energy to the earth's surface and for plant photosynthesis (Yu and Sun, 2006). Seasonal variation in radiation directly affects seasonal variations in plant photosynthetic processes (Chapin et al., 2011). In addition, diurnal, seasonal, and interannual variations in radiation also affect diurnal, seasonal, and interannual variations in temperature (Scott and Timothy, 2017). The seasonal dynamic of astronomical radiation in the northern hemisphere shows differently as the variation of latitude (Fig. 9b). The spatial pattern of the seasonal dynamics of both total radiation and temperature, as well as precipitation.

In addition, there were significant differences in  $\alpha_{GPP}$  among different ecosystem types. Further analysis found that the difference in  $\alpha_{GPP}$  among ecosystem types was mainly affected by the geographical location of ecosystems. For example, 67% of the sites in EBF with the highest average value of  $\alpha_{GPP}$  were located in the low latitudes (below 30°N), while 89% and 85% of the sites in DBF and wetlands with the lowest average value of  $\alpha_{GPP}$  were located at 40°N and north, respectively.

While part of the spatial variation in  $\alpha_{GPP}$  was explained by spatial variation in the seasonal dynamic of astronomical radiation, the spatial variation in  $\alpha_{GPP}$  could not be fully explained. It is generally believed that although radiation is the resource for photosynthesis of vegetation, it is not a restrictive factor for photosynthesis, while the limiting factors for vegetation are temperature and precipitation (Chapin et al., 2011).

The dependence of the seasonal dynamics of GPP on astronomical radiation in different regions is constrained by temperature and precipitation.

In the subtropical zone, where there are sufficient water and heat, the seasonal dynamic of GPP is similar to that of astronomical radiation (Fig. 9a, b), indicating that the seasonal dynamic of GPP in this zone is constrained by the seasonal dynamic of astronomical radiation. In the mid-latitude zone with the synchronous hydrothermal conditions, the seasonal dynamic of GPP follows a unimodal curve. The temperature limits the growing season length of vegetation in this zone, and the growing season length gradually decreases with the increase of latitude (Anay et al., 2013; Ganguly et al., 2010; Jeong et al., 2011). Thus, the seasonal dynamic of GPP is mainly affected by the seasonal dynamic of temperature, while the dependence on the seasonal dynamic of astronomical radiation is reduced. In the higher latitudes, the growing season length and the GPP<sub>max</sub> decrease because of the constraint of temperature, and the GPP<sub>max</sub> shows a similar trend with the highest temperature, which decreases with increasing latitude (Fig. 9a, c). Therefore, the dependence of seasonal dynamic of GPP on that of astronomical radiation is further reduced.

Distance from the sea (continentality), topographical factors, and whether temperature and precipitation are synchronized can also influence the seasonal dynamic of GPP. Therefore, even at the same latitude, there will be differences in environmental conditions and seasonal dynamics of climatic variables in different zones, which will lead to differences in seasonal dynamics of GPP in different zones at the same latitude. For example, there is a significant difference between the seasonal dynamics of GPP in the site "IT-RO1" in the Mediterranean climatic zone and the site "CN-CBF" in the continental zone, which are at the same latitude (42.40°N) (Fig. A8). Because of the asynchronous hydrothermal condition in site "IT-RO1" with hot dry summer and warm humid winter (Giorgi and Lionello, 2008), the daily GPP follows a bimodal curve throughout the year; the synchronous hydrothermal condition in site "CN-CBF" with cold dry winter and hot rainy summer leads to the unimodal bell-shaped curve of daily GPP. The difference in seasonal dynamics of GPP is the main reason that the  $\alpha_{Gi}$  of IT-RO1 and CN-CBF are 0.69 and 0.59, respectively.

We also found that, while GPP seemed to follow stable seasonal dynamics over several years,  $\alpha_{GPP}$  was not a constant because of the small fluctuations in the attribute parameters of GPP (GPP<sub>max</sub>, GPP<sub>mean</sub>, and CUP). For example, CUP varies with the advances or delays in vegetation physiological phenology (Piao et al., 2006, 2007, 2011) and GPP<sub>max</sub> changes with the enhancements or weaknesses in the photosynthetic capacity (Niu et al., 2011; Stoy et al., 2014; Wu et al., 2013; Xia et al., 2015; Zhou et al., 2017).

However, the  $\alpha_{GPP}$  fluctuated gently, which indicated that the seasonal dynamics of climatic variables were relatively stable over time in any specific location, even though climatic variables may vary greatly (Scott and Timothy, 2017; Zuo et al., 1991; Yao, 1959; Yu et al., 2006). In a given geographical location, if there are no special extreme climatic events, there are little variations in the seasonal dynamics of climatic variables although temperature and precipitation fluctuate between years. Therefore, the seasonal dynamics of GPP are relatively stable on an interannual scale, as well as the  $\alpha_{GPP}$ . The AGPP and the seasonal dynamic of GPP will vary significantly when a special extreme climate event occurs, but it will gradually return to its original state when the event ends (Ciais et al., 2005).

#### 4.3. The application of $\alpha_{GPP}$ for the estimation of the spatiotemporal twodimensional variation of AGPP

In this study, we defined an attribute parameter of the seasonal dynamic of GPP,  $\alpha_{GPP}$ , and discussed the biogeographic mechanism of spatial and interannual variations of  $\alpha_{GPP}$ . Through  $\alpha_{GPP}$ , the

theoretical equation (Eq. (1)) based on GPP<sub>mean</sub> and CUP could be transformed into to the theoretical equation (Eq. (2)) based on GPP<sub>max</sub>,  $\alpha_{GPP}$ , and CUP, which provided a new approach for the assessment of the spatiotemporal variation of AGPP.

Therefore, the AGPP of an ecosystem in a certain geographical location at a given year could be expressed as the product of the three attribute parameters (GPP<sub>max</sub>, CUP, and  $\alpha_{GPP}$ ) of the seasonal dynamic of GPP:

$$AGPP_{ij} = \alpha_{Gij} \times GPP_{maxij} \times CUP_{ij}$$
  
=  $\alpha_{Gi} \times (GPP_{maxi} + \Delta GPP_{maxij}) \times (CUP_i + \Delta CUP_{ij})$  (19)

And the spatial and interannual components could be expressed as Eq. (20) and Eq. (21), respectively:

$$AGPP_{i} = \frac{\sum_{1}^{n} (\alpha_{Gij} \times GPP_{maxij} \times CUP_{ij})}{n}$$
(20)

$$\Delta AGPP_{ij} = AGPP_{ij} - AGPP_i \tag{21}$$

CUP was a phenological parameter of an ecosystem that was mainly affected by temperature (Hu et al., 2010; Jeong et al., 2011; Piao et al., 2006), and could be estimated using a function of temperature. GPP<sub>max</sub> was the maximum value that daily GPP in an ecosystem could achieve in a year, which was mainly affected by climatic variables (Allard et al., 2008; Hirata et al., 2007; Saigusa et al., 2008; Stoy et al., 2014). The  $a_{Gi}$  was mainly affected by hile the  $a_{Qi}$  was determined by latitude so that the  $a_{Gi}$  could be estimated by latitude.

Therefore, the mechanism showed in Eq. (19) is that the spatial and interannual variations of climatic variables affect the spatiotemporal two-dimensional variation of AGPP through the influences on the spatial and interannual variations of phenology and photosynthesis abilities of vegetation. According to the spatiotemporal variation of seasonal dynamic attribute parameters of GPP, a model could be established to assess AGPP based on the theoretical relationship of "seasonal dynamics of environmental variables - the seasonal dynamic of GPP - accumulation process of AGPP". Here we only used the functions that expressed the spatial variations of  $\alpha_{GPP}$ , CUP, and GPP<sub>max</sub> to estimate the spatial variation of *AGPP<sub>i</sub>* (the spatial component of AGPP) preliminarily. Then the Eq. (20) could be expressed as:

$$AGPP_i = \alpha_{Gi} \times GPP_{maxi} \times CUP_i$$
<sup>(22)</sup>

Here we only used the spatial components of three climatic variables  $(AMT_i, ATP_i \text{ and } ATR_i)$  to assess the spatial components of CUP and GPP<sub>max</sub>. The empirical equations were:

 $CUP_i = 186.81 + 6.329 \times AMT_i, \quad n = 115, R^2 = 0.48, P < 0.0001$  (23)

$$\begin{aligned} \text{GPP}_{maxi} &= 0.185 \times AMT_i + 2.127 \times \ln(ATP_i) - 0.022 \times AMT_i \times \ln(ATP_i) \\ &- 5.694 \times 10^{-5} \times ATR_i - 2.565, \quad n = 115, \ r^2 = 0.34, \ P < 0.0001 \end{aligned} \tag{24}$$

where  $AMT_i$  was the spatial component of annual mean temperature,  $ATP_i$  was the spatial component of annual total precipitation,  $ATR_i$  was the spatial component of annual total radiation.

Combined the Eq. (22) with the Eqs. (18), (23), and (24), the spatial variation of  $AGPP_i$  could be estimated. The result showed that the  $r^2$  of this model was 0.58, and the rmse was 451.17 (Fig. 10), indicating that the approach proposed in this study had the application potential to assess AGPP. However, the estimations of GPP<sub>max</sub>, CUP, and  $\alpha_{GPP}$  in this study were very simple and preliminary with great uncertainty. For example, the accuracy of the estimation of the parameter was low (the  $r^2$  of GPP<sub>max</sub> was only 0.34). Therefore, we will optimize the model with new climatic indicators and new functions in the future for a more comprehensive understanding and accurate assessment of the spatio-temporal variation of AGPP.



Fig. 10. The relationship between AGPP<sub>i</sub> estimated by the model in this study and observed AGPP<sub>i</sub>. AGPP<sub>iest</sub> is AGPP<sub>i</sub> calculated based on the model in this study, AGPPiobs is the observed AGPPi.

#### 5. Conclusion

In this study, we proposed an attribute parameter ( $\alpha_{GPP}$ ), which was defined as the ratio of the mean daily GPP (GPP\_{mean}) to the maximum daily GPP (GPP<sub>max</sub>) of the ecosystem during the growing season, to quantitatively describe the seasonal dynamic of GPP. The  $\alpha_{GPP}$  was a comprehensive parameter characterizing the shape, scale, and location of the seasonal dynamic of GPP. We calculated the  $\alpha_{GPP}$ of terrestrial ecosystems in the Northern Hemisphere based on flux data, and compared the differences of the  $\alpha_{GPP}$  in different climatic zones and different ecosystem types. Then we analyzed the spatial and temporal variations of the  $\alpha_{\text{GPP}}$  and explained which climatic variables controlled the spatial variation of  $\alpha_{GPP}$ . Moreover, we developed a preliminary biogeographic model for estimating the spatial variation of AGPP based on the spatial variation of  $\alpha_{GPP}$ , which demonstrated the potential of developing a biogeographic model to assess the spatiotemporal two-dimensional variation of AGPP based on the theoretical relationship of "seasonal dynamics of environmental variables the seasonal dynamic of GPP - accumulation process of AGPP". The results showed that:

(1) The average value of  $\alpha_{\text{GPP}}$  of the terrestrial ecosystems in the Northern Hemisphere was  $0.62 \pm 0.06$ , the maximum value was 0.85, and the minimum value was 0.47. The mean value of

## Appendices

 $\alpha_{GPP}$  in the tropical zone was the largest and the variability was the smallest, the mean value of  $\alpha_{GPP}$  in the continental zone was the smallest, and the variability of  $\alpha_{GPP}$  in the Mediterranean climatic zone was the largest. The average value of  $\alpha_{GPP}$  in evergreen broad-leaved forests was the largest, the average values of  $\alpha_{\text{GPP}}$  in deciduous broad-leaved forests and wetlands were the smallest and the variabilities in these two types were the largest.

- (2) Due to the relative stability of the seasonal dynamics in climatic variables on the interannual scale,  $\alpha_{GPP}$  was relatively stable between years. The  $\alpha_{GPP}$  decreased with the increase of latitude, which was mainly affected by the spatial pattern of the seasonal dynamic in astronomical radiation. The spatial pattern of seasonal dynamic in astronomical radiation affected the spatial pattern of seasonal dynamics in total radiation and temperature, and finally determined the spatial pattern of  $\alpha_{GPP}$ .
- (3) The model based on the spatial patterns of CUP, GPP<sub>max</sub> and  $\alpha_{GPP}$  could assess the spatial pattern of AGPP preliminarily, which proved the practicability of estimating the spatial and temporal variations of AGPP based on the seasonal dynamic parameters of GPP. However, the work in this study is still simple and preliminary, it is necessary to further optimize the model with new climatic indicators and new functional forms in the future.

#### Acknowledgments

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Further analysis of the seasonal dynamic curve of GPP fitted by Weibull function showed that when t was x<sub>0</sub>, which was the time that the first derivative of function was 0, daily GPP reached the maximum value ( $t_{max} = x_0$ ), and the maximum value was the peak of the GPP curve:

$$GPP_{max} = f(x_0) = y_0 + \eta$$

Then AGPP was calculated as the integrated value of the Weibull function during the CUP (from  $t_1$  to  $t_2$ ) as shown in Eq. A2:

$$AGPP = \int_{t_1}^{t_2} f(t)dt = \eta \left(\frac{k-1}{k}\right)^{\frac{1-k}{k}} e^{\frac{k-1}{k}} \cdot \frac{-\lambda}{k} \left( e^{-\left[\frac{t_2-x_0}{\lambda} + \left(\frac{k-1}{k}\right)^{\frac{1}{k}}\right]^k} - e^{-\left[\frac{t_1-x_0}{\lambda} + \left(\frac{k-1}{k}\right)^{\frac{1}{k}}\right]^k} \right)^{\frac{1}{k}}$$

Thus, the GPP<sub>mean</sub> was:

$$GPP_{mean} = \frac{\eta\left(\frac{k-1}{k}\right)^{\frac{1-k}{k}}e^{\frac{k-1}{k}} \cdot \frac{-\lambda}{k} \left(e^{-\left[\frac{t_2-x_0}{\lambda} + \left(\frac{k-1}{k}\right)^{\frac{1}{k}}\right]^k} - e^{-\left[\frac{t_1-x_0}{\lambda} + \left(\frac{k-1}{k}\right)^{\frac{1}{k}}\right]^k}\right)}$$

(

(A3)

(A1)

(A2)

Therefore,  $\alpha_{GPP}$  was:

$$\alpha_{GPP} = \frac{GPP_{mean}}{GPP_{max}} = \frac{\eta \left(\frac{k-1}{k}\right)^{\frac{1-k}{k}} e^{\frac{k-1}{k} \cdot \frac{-\lambda}{k}} \left( e^{-\left[\frac{t_2 - x_0}{\lambda} + \left(\frac{k-1}{k}\right)^{\frac{1}{k}}\right]^k} - e^{-\left[\frac{t_1 - x_0}{\lambda} + \left(\frac{k-1}{k}\right)^{\frac{1}{k}}\right]^k} \right)}$$
(A4)

The  $t_2$  and  $t_1$  in Eq. A4 are the start day and the end day of CUP, respectively. The  $x_0$  is the time when daily GPP reaches GPP<sub>max</sub>, and could be marked as  $t_{max}$ . The difference between  $t_2$  and  $t_1$  ( $t_2$ - $t_1$ ) is CUP; the difference between  $t_{max}$  and  $t_1$  ( $t_{max}$ - $t_1$ ) is the period when daily GPP increases and could be marked as CUP1; the difference between tmax and t2 (t2-tmax) is the period when daily GPP decreases and could be marked as CUP2. If CUP1 is equal to CUP<sub>2</sub>, the seasonal dynamic curve is the symmetric bell curve (Fig. A7a), otherwise, it is an asymmetric bell curve. If CUP<sub>1</sub> < CUP<sub>2</sub>, the period when daily GPP increased is shorter than that when daily GPP decreased, indicating the faster growth and slower senescence (Fig. A7b); if CUP1 > CUP2, the period when daily GPP decreased is shorter than that when daily GPP increased, indicating the slower growth and faster senescence (Fig. A7c). When the second derivative is equal to zero, that is: f''(t) = 0

Then:

$$t_{01} = \left[ 2^{\frac{-1}{k}} \times \left( \frac{(3k^2 - 3k) - k \times \sqrt{1 - 6k + 5k^2}}{k^2} \right)^{\frac{1}{k}} - \left( \frac{k - 1}{k} \right)^{\frac{1}{k}} \right] \times \lambda + x_0$$
(A5)

$$t_{02} = \left[ 2\frac{-1}{k} \times \left( \frac{(3k^2 - 3k) + k \times \sqrt{1 - 6k + 5k^2}}{k^2} \right)^{\frac{1}{k}} - \left( \frac{k - 1}{k} \right)^{\frac{1}{k}} \right] \times \lambda + x_0$$
(A6)  
If:

$$V_{01} = 2^{\frac{-1}{k}} \times \left(\frac{(3k^2 - 3k) - k \times \sqrt{1 - 6k + 5k^2}}{k^2}\right)^{\frac{1}{k}}$$
(A7)  
$$V_{02} = 2^{\frac{-1}{k}} \times \left(\frac{(3k^2 - 3k) + k \times \sqrt{1 - 6k + 5k^2}}{k^2}\right)^{\frac{1}{k}}$$
(A8)

Then the Eq. A5 and Eq. A6 could be expressed as:

$$t_{01} = \left[ V_{01} - \left(\frac{k-1}{k}\right)^{\frac{1}{k}} \right] \times \lambda + x_0 \tag{A9}$$



Fig. A1. Autocorrelation coefficients of  $\alpha_{GPP}$  at each site. Each polyline represents a site, and the points on the polyline represent the autocorrelation coefficients in the site; the red and blue lines in the figure represent 2 standard deviations, where the red lines represent 2 times the standard deviation of the red sites, and the blue lines represent 2 times the standard deviation of the blue sites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

)



Fig. A2. The coefficient of variation in each site.



**Fig. A3.** Relationships between  $\alpha_{Gi}$  with (a)  $AMT_b$  (b)  $ATP_b$  (c)  $ATR_b$  (d)  $\alpha_{Qib}$  (e)  $\alpha_{Tib}$  and (f)  $\alpha_{Ri}$ . \*\*\* indicates P < 0.001.  $AMT_b$   $ATP_i$  and  $ATR_i$  are the spatial components of annual mean temperature, annual total precipitation, and annual total radiation;  $\alpha_{Qb}$   $\alpha_{Tb}$   $\alpha_{Ri}$  and  $\alpha_{Gi}$  are the spatial components of the seasonal dynamic parameters of astronomical radiation, temperature, total radiation and GPP.

$$t_{02} = \left[ V_{02} - \left(\frac{k-1}{k}\right)^{\frac{1}{k}} \right] \times \lambda + x_0 \tag{A10}$$

Then:

 $\Delta t = t_{02} - t_{01} = \lambda \times (V_{02} - V_{01}) \tag{A11}$ 

And the f(t) at  $t_{01}$  and  $t_{02}$  are:

$$f(t_{01}) = y_0 + \eta \times \left(\frac{k-1}{k}\right)^{\frac{1-k}{k}} \times V_{01}^{k-1} \times e^{\frac{k-1}{k} - V_{01}^k}$$
(A12)

$$f(t_{02}) = y_0 + \eta \times \left(\frac{k-1}{k}\right)^{\frac{1-k}{k}} \times V_{02}^{k-1} \times e^{\frac{k-1}{k} - V_{02}^k}$$
(A13)

If:

$$Z_1 = \left(\frac{k-1}{k}\right)^{\frac{1-k}{k}} \times V_{01}^{k-1} \times e^{\frac{k-1}{k} - V_{01}^k}$$
(A14)



Fig. A4. The scale parameter (a, c, e) and location parameter (b, d, f) in x-axis. (c) and (d) are the first derivative; (e) and (f) are the second derivative.

$$Z_{2} = \left(\frac{k-1}{k}\right)^{\frac{1-k}{k}} \times V_{02}^{k-1} \times e^{\frac{k-1}{k}} - V_{02}^{k}$$
(A15)  
Then:  

$$f(t_{01}) = y_{0} + \eta \times Z_{1}$$
(A16)  

$$f(t_{02}) = y_{0} + \eta \times Z_{2}$$
(A17)

 $P_1$  ( $t_{01}$ , $f(t_{01})$ ) and  $P_2$  ( $t_{02}$ , $f(t_{02})$ ) represent the maximum and minimum rate of change in the curve (Fig. A6a). The line connecting  $P_1$  and  $P_2$  ( $P_1P_2$ ) can be expressed as:

$$\frac{t - t_{01}}{t_{02} - t_{01}} = \frac{y - f(t_{01})}{f(t_{02}) - f(t_{01})}$$
(A18)

The point  $L_{max}$  represents the point in the line  $P_1P_2$ , and the value of x-axis is  $t_{max}$ . So the value of y-axis is:



Fig. A5. The scale parameter (a, c, e) and location parameter (b, d, f) in y-axis. (c) and (d) are the first derivative; (e) and (f) are the second derivative.

$$y_{max} = \frac{x_0 - t_{01}}{t_{02} - t_{01}} \times (f(t_{02}) - f(t_{01})) + f(t_{01})$$
  
=  $\frac{-V_{01} - \left(\frac{k-1}{k}\right)^{\frac{1}{k}}}{V_{02} - V_{01}} \times \eta \times (Z_2 - Z_1) + y_0 + \eta \times Z_1$  (A19)

Therefore, the distance from  $L_{max}$  to the point with maximum value,  $P_{max}\left(t_{max},\,f(t_{max})\right),$  is:

$$\Delta y = f(t_{max}) - y_{max} = y_0 + \eta - \left[\frac{-V_{01} - \left(\frac{k-1}{k}\right)^{\frac{1}{k}}}{V_{02} - V_{01}} \times \eta \times (Z_2 - Z_1) + y_0 + \eta \times Z_1\right] = \eta \times \left[1 - \frac{-V_{01} - \left(\frac{k-1}{k}\right)^{\frac{1}{k}}}{V_{02} - V_{01}} \times (Z_2 - Z_1) - Z_1\right]$$
(A20)



**Fig. A6.** The shape parameter *k*. (b) is the first derivative; (c) is the second derivative; the points in (a) represent the maximum and minimum rate of change in each curve;  $F_{\text{max}}$  represents the maximum value of curve;  $P_1$  and  $P_2$  represent the maximum and minimum rate of change in the red curve, respectively;  $L_{\text{max}}$  represents the point in the line connecting  $P_1$  and  $P_2$  where the value of x-axis is  $t_{\text{max}}$ ;  $\Delta y$  represent the distance from  $P_{\text{max}}$  to  $L_{\text{max}}$ ;  $\Delta t$  represents the distance from  $P_1$  to  $P_2$  in x-axis.

(A22)



**Fig. A7.** The periods when daily GPP increases (CUP<sub>1</sub>) and decreases (CUP<sub>2</sub>). (a) represents the symmetric curve where CUP<sub>1</sub> is equal to CUP<sub>2</sub>; (b) represents the asymmetric curve where CUP<sub>1</sub> < CUP<sub>2</sub>; (c) represents the asymmetric curve where CUP<sub>1</sub> > CUP<sub>2</sub>;  $t_1$ ,  $t_2$ , and  $t_{max}$  represent the start day, the end day, and the day when the maximum value occurs, respectively; GPP<sub>max</sub> represents the maximum value of the curve.



Fig. A8. Seasonal variations in (a, d) GPP, (b, e) astronomical radiation, (c, f) temperature and precipitation at IT-RO1 and at CN-CBF. (a), (b), and (c) represent the site IT-RO1; (d), (e), and (f) represent the site CN-CBF.

Here we use the ratio of  $\Delta y$  to  $\Delta t$  to express the proportional relationship between the x-axis and the y-axis quantificationally:

$$\frac{\Delta y}{\Delta t} = \frac{\eta \times \left[1 - \frac{-V_{01} - \left(\frac{k-1}{k}\right)^{\frac{1}{k}}}{V_{02} - V_{01}} \times (Z_2 - Z_1) - Z_1\right]}{\lambda \times (V_{02} - V_{01})} = \frac{\eta}{\lambda} \times \frac{\left[1 - \frac{-V_{01} - \left(\frac{k-1}{k}\right)^{\frac{1}{k}}}{V_{02} - V_{01}} \times (Z_2 - Z_1) - Z_1\right]}{(V_{02} - V_{01})}$$
(A21)  
Where 
$$\frac{\left[1 - \frac{-V_{01} - \left(\frac{k-1}{k}\right)^{\frac{1}{k}}}{V_{02} - V_{01}} \times (Z_2 - Z_1) - Z_1\right]}{(V_{02} - V_{01})}$$
is the function of k.  
Then:

 $\frac{\Delta y}{\Delta t} = \frac{\eta}{\lambda} \times F(k)$ 

Therefore,  $\Delta y / \Delta t$  is the function of the shape parameter and the scale parameters of x-axis and y-axis (Fig. A6a).

## Table A.1

Information of sites used in this study.

Site	Ecosystem	Lat	Lon	Year	References
AT-Neu	Grassland	47.12	11.32	2002–2012	Wohlfahrt et al., 2008
BE-Bra	MF	51.31	4.52	1999-2002,2004-2014	Carrara et al., 2004
BE-Vie	MF	50.31	6	1997–2014	Aubinet et al., 2001
CA-Gro	MF	48.22	-82.16	2003-2013	McCaughey et al., 2006
CA-Man	ENF	55.88	- 98 48	1994-2003 2007	Dunn et al 2007
CA-NS1	ENF	55.88	- 98 48	2002-2004	Goulden et al 2006
CA NS2	ENE	55.00	- 08 28	2002-2004	Goulden et al. 2006
CA-NS5	ENF	55.91	- 96.36	2001-2005	Coulden et al. 2006
CA-N54	ENF	55.91	- 98.38	2002-2005	
CA-NS5	ENF	55.86	- 98.49	2002-2005	Goulden et al., 2006
CA-NS6	Shrubland	55.92	- 98.96	2001-2005	Goulden et al., 2006
CA-NS7	Shrubland	56.64	- 99.95	2003–2005	Goulden et al., 2006
CA-Oas	DBF	53.63	-106.2	1996–2010	Schmidt et al., 2011
CA-Obs	ENF	53.99	-105.12	1999–2010	Bergeron et al., 2007
CA-Qfo	ENF	49.69	-74.34	2004–2010	Bergeron et al., 2007
CA-SF2	ENF	54.25	-105.88	2001-2005	Mkhabela et al., 2009
CA-SF3	Shrubland	54.09	-106.01	2002-2006	Mkhabela et al., 2009
CA-TP1	ENF	42.66	- 80 56	2006-2010 2012-2014	Peichl et al 2010
CA-TP3	ENF	42.00	- 80.35	2003_2005_2007_2014	Peichl et al. 2010
CA-TP4	ENF	42.71	- 00.33	2003-2003,2007-2014	Arein and Bestrand Course 2005
CA-1P4	ENF	42./1	- 80.30	2003-2014	Atam and Restrepo-Coupe, 2005
CA-1PD		42.04	- 80.56	2012-2014	Schinicit et al., 2011
CH-Cha	Grassland	47.21	8.41	2005-2014	Merbold et al., 2014
CH-Dav	ENF	46.82	9.86	1997–2014	Zielis et al., 2014
CH-Fru	Grassland	47.12	8.54	2006-2008,2010-2014	Imer et al., 2013
CH-Lae	MF	47.48	8.37	2004–2014	Etzold et al., 2011
CH-Oe1	Grassland	47.29	7.73	2002–2008	Ammann et al., 2009
CN-Cng	Grassland	44.59	123.51	2007-2010	Dong.2016
CN-HaM	Grassland	37.37	101.18	2002–2004	Kato et al., 2006
CZ-BK2	Grassland	49.49	18.54	2006-2012	Pavelka et al., 2007
CZ-wet	Wetland	49.02	14 77	2006_2014	Dusek et al. 2012
DE Alem	Wetland	F2 07	12.60	2000-2014	Busck et al., 2012
DE-AKIII	wettand	53.87	13.08	2010-2014	Bernholer et al.,2016a
DE-Gri	Grassland	50.95	13.51	2004-2014	Prescher et al., 2010
DE-Hai	DBF	51.08	10.45	2000-2012	Knohl et al., 2003
DE-Lkb	ENF	49.1	13.3	2010–2013	Lindauer et al., 2014
DE-Lnf	DBF	51.33	10.37	2002-2006,2010-2012	Anthoni et al., 2004
DE-Obe	ENF	50.78	13.72	2008–2014	Bernhofer et al.,2016b
DE-RuR	Grassland	50.62	6.3	2011-2014	Post et al., 2015
DE-SfN	Wetland	47.81	11.33	2012-2014	Hommeltenberg et al., 2014
DE-Spw	Wetland	51.89	14.03	2011-2014	Bernhofer et al.,2016c
DE-Tha	ENF	50.96	13.57	1997-2014	Gruenwald and Bernhofer, 2007
DK-NuF	Wetland	64.13	- 51 39	2009_2013	Westergaard-Nielsen et al. 2013
DK Sor	DRE	55.40	11.64	1007 2014	Bilegaard et al. 2011
DK-301	Motion d	74.49	20 55	2009 2011	Cooperation of Nordetreem 1000
DK-ZaF	Wettand Grandland	74.48	- 20.55	2008-2011	Soegaard and Nordstroem, 1999
DK-ZaH	Grassland	/4.4/	- 20.55	2000,2002,2008-2010,2012-2014	Lund et al., 2012
ES-LJu	Shrubland	36.93	-2.75	2010-2011,2013	Serrano-Ortiz et al., 2009
FI-Hyy	ENF	61.85	24.3	1997–2014	Suni et al., 2003
FI-Let	ENF	60.64	23.96	2009–2012	Koskinen et al., 2014
FI-Lom	Wetland	68	24.21	2007–2009	Aurela et al., 2015
FI-Sod	ENF	67.36	26.64	2001–2014	Thum et al., 2007
FR-Fon	DBF	48.48	2.78	2005-2014	Delpierre et al., 2016
FR-LBr	ENF	44.72	-0.77	1996-1997,1999-2008	Berbigier et al., 2001
FR-Pue	EBF	43.74	3.6	2002-2006,2008.2010-2013	Rambal et al., 2010
GF-Guy	EBF	5.28	- 52 92	2004–2014	Bonal et al., 2008
IT-CA1	DBF	42.38	12.03	2011-2012.2014	Sabbatini et al 2016
IT-Col	DBF	41.95	13 50	1997-2001 2005-2014	Valentini et al. 1006
	LDL	41.00	10.07	1997-2001,2000-2014	Forme at cl. 2014
11-Ср2	EDF	41./	12.30	2012-2014	Fares et al., 2014
11-Cpz	EBF	41.71	12.38	2000-2007	Garbulsky et al., 2008
IT-Lav	ENF	45.96	11.28	2003–2014	Marcolla et al., 2003
IT-MBo	Grassland	46.01	11.05	2003–2013	Marras et al., 2011
IT-Noe	Shrubland	40.61	8.15	2004-2007,2009-2010,2012-2014	Marras et al., 2011
IT-PT1	DBF	45.2	9.06	2002–2004	Migliavacca et al., 2009
IT-Ren	ENF	46.59	11.43	1999,2002-2003,2005-2013	Montagnani et al., 2009
IT-Ro1	DBF	42.41	11.93	2001–2008	Rey et al., 2002
IT-Ro2	DBF	42.39	11.92	2002-2008.2010-2012	Tedeschi et al., 2006
IT-SRo	ENF	43 73	10.28	2000-2012	Chiesi et al 2005
IT-Tor	Graceland	45.94	7 58	2009-2014	Galvarno et al 2012
ID CME	ME	40.04	1.00	2007-2017	Mataumota et al. 2000
JP-5MF	MF	35.26	137.08	2002-2006	Matsumoto et al., 2008
MY-PSO	EBF	2.97	102.31	2003-2009	Kosugi et al., 2008
NL-Hor	Grassland	52.24	5.07	2005–2010	Jacobs et al., 2007
NL-Loo	ENF	52.17	5.74	1996–2014	Moors, 2012
PA-SPn	DBF	9.32	-79.63	2007–2009	Wolf et al., 2011
RU-Cok	Shrubland	70.83	147.49	2003,2008-2010,2012	Van der Molen et al., 2007
RU-Fvo	ENF	56.46	32.92	1999-2001,2003-2014	Kurbatova et al., 2008
RU-Sam	Grassland	72.37	126 5	2006 2008-2009 2013	Boike et al 2013
RU-SkP	DNF	62.26	120.0	2012-2014	Dolman et al. 2012: Kotani et al. 2014
	~~		/		2011 and a any 2012, noturn of all, 2017

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#### Table A.1 (continued)

Site	Ecosystem	Lat	Lon	Year	References
US-AR2	Grassland	36.64	- 99.6	2009-2010,2012	Raz-Yaseef et al., 2015
US-Atq	Wetland	70.47	-157.41	2004–2008	Oechel et al., 2014
US-Blo	ENF	38.9	-120.63	2001–2007	Goldstein and Schade, 2000
US-Cop	Grassland	38.09	-109.39	2003,2006-2007	Schmidt et al., 2011
US-GLE	ENF	41.37	-106.24	2005–2014	Frank et al., 2014
US-Goo	Grassland	34.25	- 89.87	2003–2004,2006	Schmidt et al., 2011
US-Ha1	DBF	42.54	-72.17	1992–2012	Urbanski et al., 2015
US-IB2	Grassland	41.84	-88.24	2005–2011	Matamala et al., 2008
US-Ivo	Wetland	68.49	-155.75	2004–2007	Mcewing et al., 2015
US-KS2	Shrubland	28.61	-80.67	2003–2006	Powell et al., 2006
US-Los	Wetland	46.08	- 89.98	2001–2008, 2010, 2014	Sulman et al., 2009
US-Me2	ENF	44.45	-121.56	2002, 2004–2014	Irvine et al., 2008
US-Me3	ENF	44.32	-121.61	2004–2006, 2008	Vickers et al., 2009
US-Me4	ENF	44.5	-121.62	1996–1997, 1999	Law et al., 2001
US-Me5	ENF	44.44	-121.57	2000–2002	Irvine et al., 2004
US-Me6	ENF	44.32	-121.61	2011–2013	Ruehr et al., 2012
US-MMS	DBF	39.32	-86.41	1999–2014	Dragoni et al., 2011
US-Myb	Wetland	38.05	-121.77	2012–2014	Matthes et al., 2014
US-NR1	ENF	40.03	-105.55	1999–2014	Monson et al., 2002
US-Oho	DBF	41.55	-83.84	2004–2013	Noormets et al., 2008
US-PFa	MF	45.95	-90.27	1996–2014	Desai et al., 2015
US-Prr	ENF	65.12	-147.49	2011,2013-2014	Ikawa et al., 2014; Nakai et al., 2013
US-Syv	MF	46.24	- 89.35	2001-2007,2012-2014	Desai et al., 2005
US-UMB	DBF	45.56	-84.71	2000-2014	Gough et al., 2013
US-UMd	DBF	45.56	-84.7	2008–2014	Gough et al., 2013
US-Var	Grassland	38.41	-120.95	2001-2003,2005,2007-2010,2013-2014	Ma et al., 2007
US-WCr	DBF	45.81	-90.08	2000-2006,2011-2014	Cook et al., 2004
US-Wkg	Grassland	31.74	-109.94	2006,2008,2010-2014	Scott et al., 2010
US-WPT	Wetland	41.46	- 83	2011–2013	Chu et al., 2015
CN-BNF	EBF	21.96	101.21	2003–2012	-
CN-CBF	MF	42.4	128.1	2003–2011	-
CN-DHF	EBF	23.17	112.54	2003–2012	-
CN-DXG	Grassland	30.5	91.07	2004–2011	-
CN-HBG	Shrubland	37.67	101.33	2003–2012	-
CN-HBW	Wetland	37.61	101.32	2003–2012	-
CN-NMG	Grassland	43.53	116.67	2004-2005,2007-2008,2010-2012	-
CN-QYF	ENF	26.75	115.06	2003–2012	-
CN-ALF	EBF	24.54	101.03	2009–2012	-
CN-DLG	Grassland	42.03	116.28	2010-2012	-
CN-HTF	EBF	26.83	109.75	2008-2012	-
CN-XLG	Grassland	43.55	116.67	2010-2012	-

DBF: deciduous broad-leaved forests; DNF: deciduous coniferous forest; EBF: evergreen broad-leaved forests; ENF: evergreen coniferous forests; MF: mixed forests.

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